Holographic Noise

Craig Hogan

Fermilab and U. Chicago

Paradoxes of “Empty Space”

- Empty space is not empty
  - Black holes are made of pure spacetime
  - Quantum fluctuations are everywhere
  - Dark Energy: most cosmic energy is in the vacuum
  - Gravitational waves carry energy everywhere
- Empty space is not even really space
  - Space and time are intertwined
- Is there a smallest interval of time and space?
- To study empty space, study empty space

Are time and space infinitely smooth?

- Einstein's theory assumes spacetime is a classical manifold, infinitely divisible
- This may be just an approximate behavior
- Can we measure the minimum interval of time?

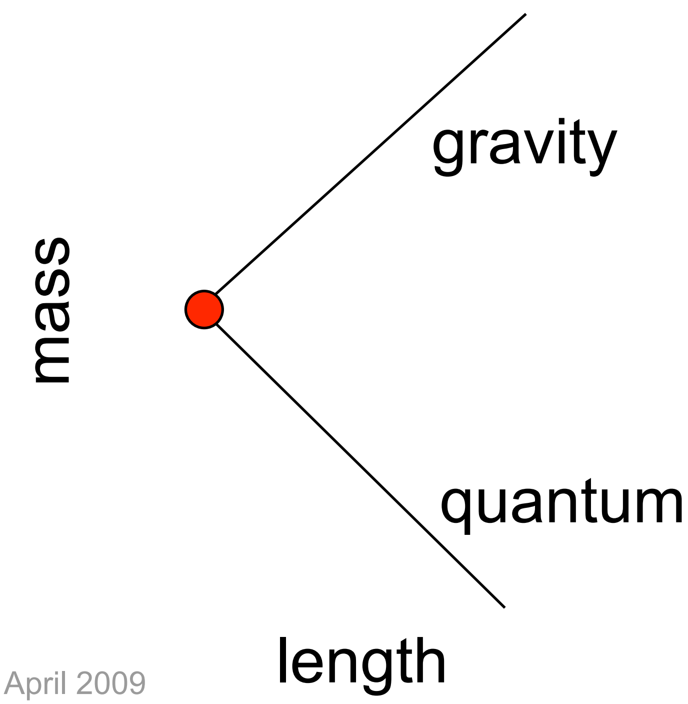
The smallest interval of time

- Quantum gravity suggests a minimum (Planck) time,

$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \quad \text{seconds}$$

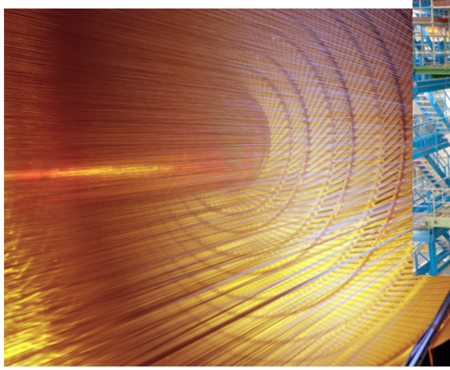
$$l_P = \sqrt{\hbar G_N/c^3} = 1.616 \times 10^{-33}\text{cm}$$

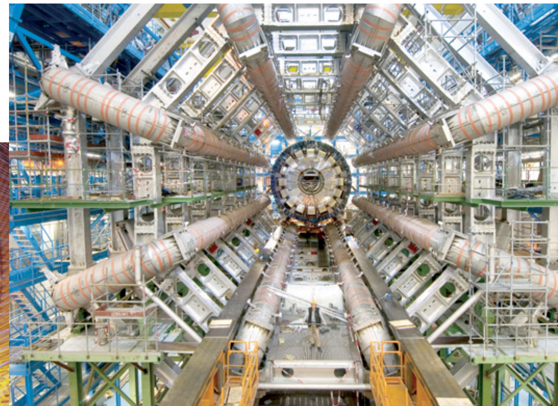
- ~ particle energy 10^{16} TeV

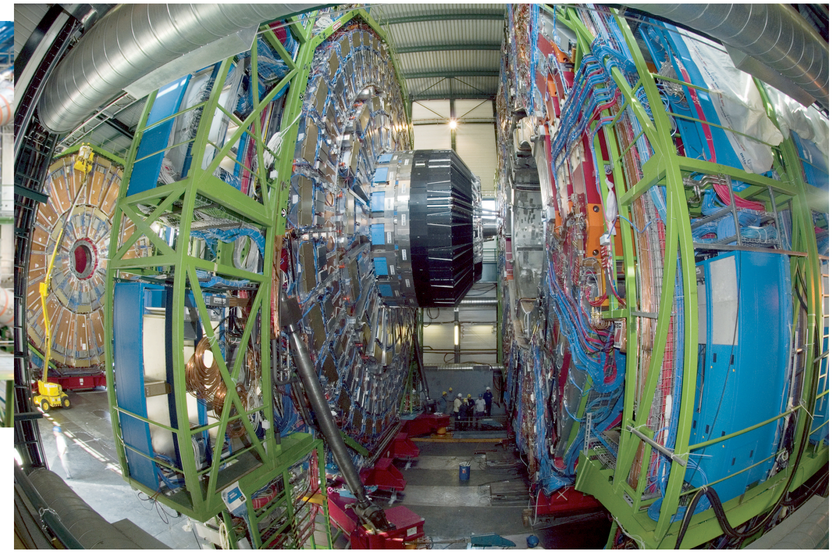


Best microscopes vs best microphones

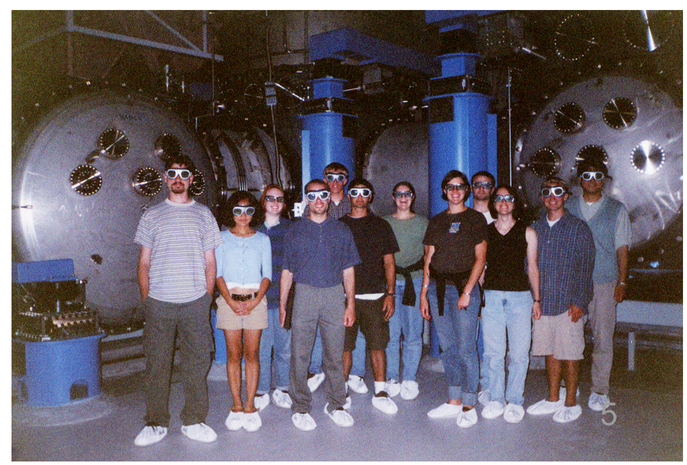
CERN/Fermilab: $\mathrm{TeV}^{-1} \sim 10^{-18}$ m: particle interactions







LIGO/GEO600: $\sim 10^{-18}$ m, coherent over $\sim 10^{3}$ m baseline: Positions of massive bodies



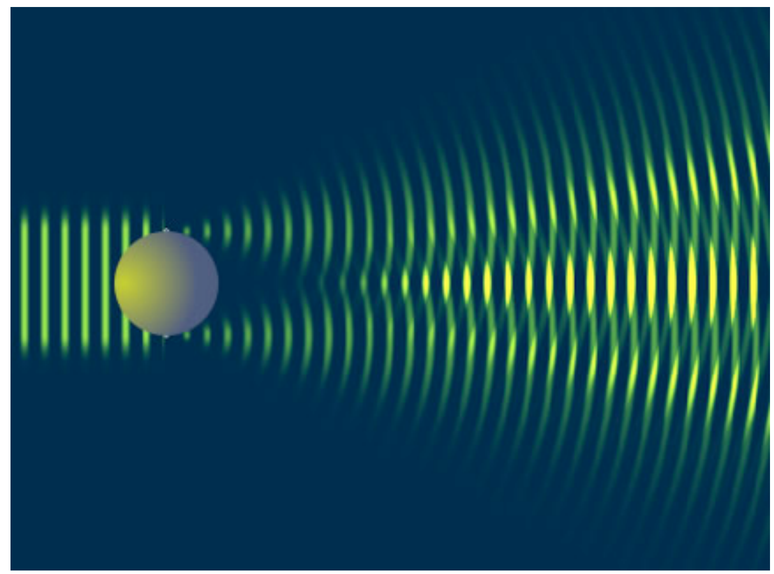
A new phenomenon?: holographic noise

- The minimum interval of time may affect interferometers
- Transverse uncertainty much larger than Planck scale in holographic theories
- precise, zero-parameter prediction of "Holographic Noise"

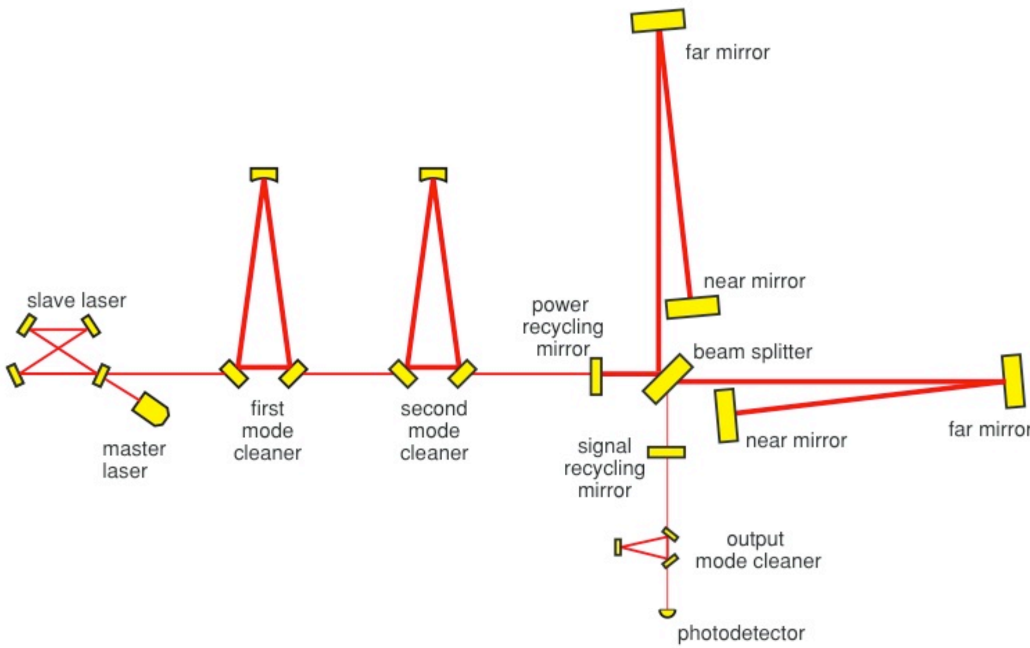
"Planck diffraction limit" at *L*

$$\Delta x \sim \sqrt{\lambda L}$$

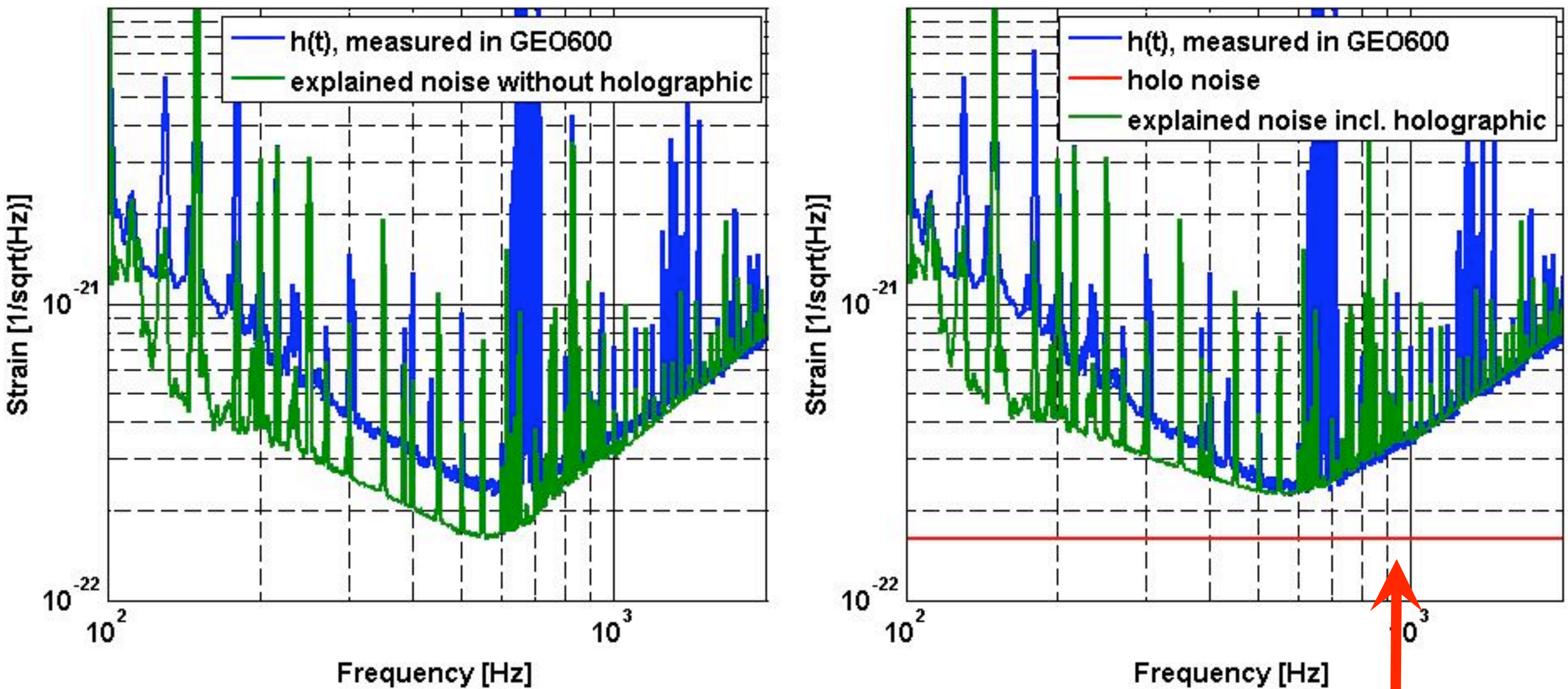
is >> Planck length



GEO-600 (Hannover): best displacement sensitivity



“Mystery Noise” in GEO600



$$\sqrt{t_{Planck}/2}$$

zero-parameter prediction for holographic noise in GEO600 (equivalent GW strain)

Data: S. Hild (GEO600)

Prediction: CJH, arXiv:0806.0665
(Phys Rev D.78.087501)

Total noise: not fitted

Measurement of holographic noise

- Holographic wave geometry predicts a new detectable effect: "holographic noise”
- Not the same as zero-point field mode fluctuations
- Spectrum and distinctive spatial character of the noise is predicted with no parameters
- It may already be detected
- An experimental program is motivated

CJH: **arXiv:0806.0665** Phys Rev D.78.087501 (2008)

CJH: **arXiv:0712.3419** Phys Rev D 77, 104031 (2008)

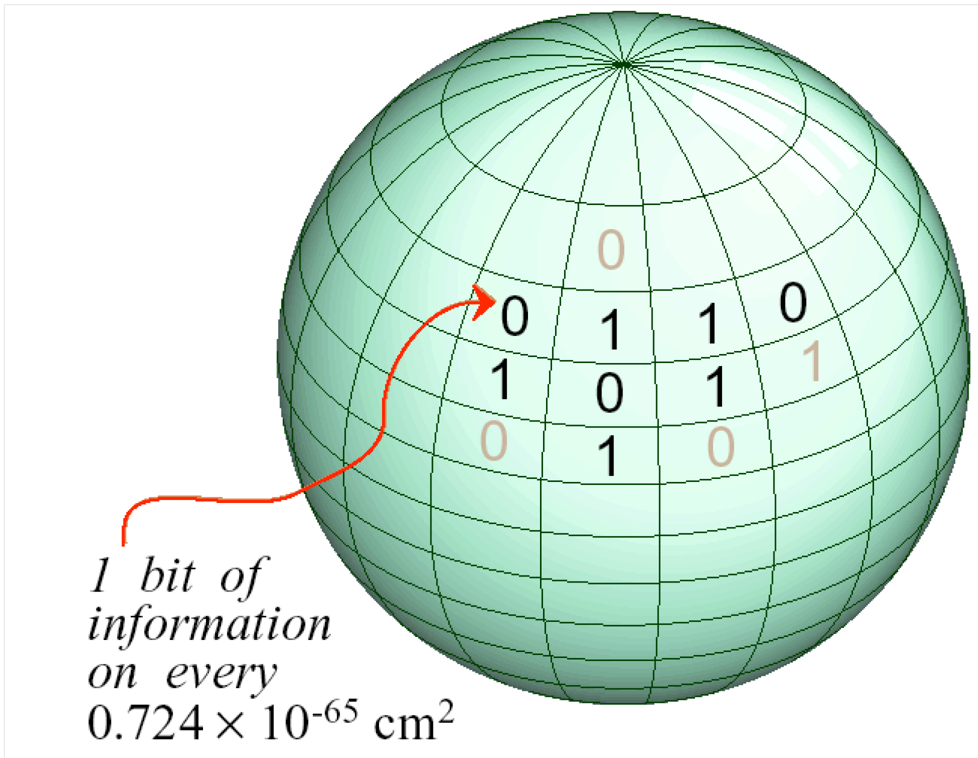
In Matrix theory: CJH and M. Jackson, arXiv:0812.1285

Holographic Theories of Everything

"This is what we found out about Nature's book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size."

-Gerard 't Hooft

Everything about the 3D world can be encoded on a 2D null surface at Planck resolution



Holographic Quantum Geometry: theory

- Black holes: entropy=area/4 $S = A/l_P^2 4 \ln 2$
- Black hole evaporation
- Einstein's equations from heat flow
- Classical GR from surface theory
- Universal covariant entropy bound
- Exact state counts of extremal holes in large D
- AdS/CFT type dualities: N-1 dimensional duals
- Matrix theory
- All suggest theory on 2+1 dimensional null surfaces with Planck frequency bound

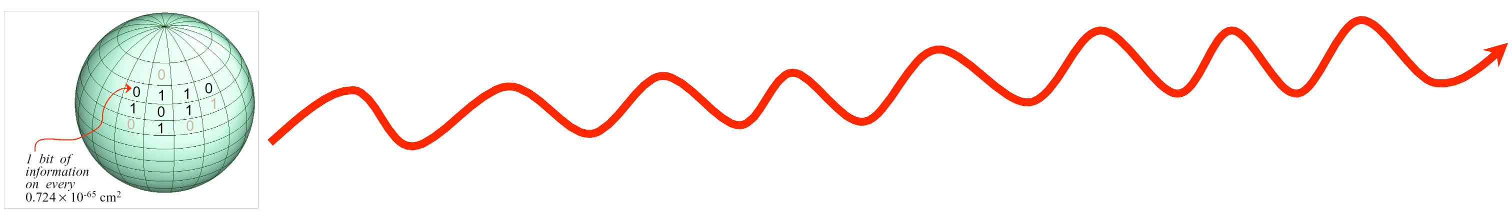
Beckenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Padmanabhan, Banks, Fischler, Shenker, Unruh

Holography 1: Black Hole Thermodynamics

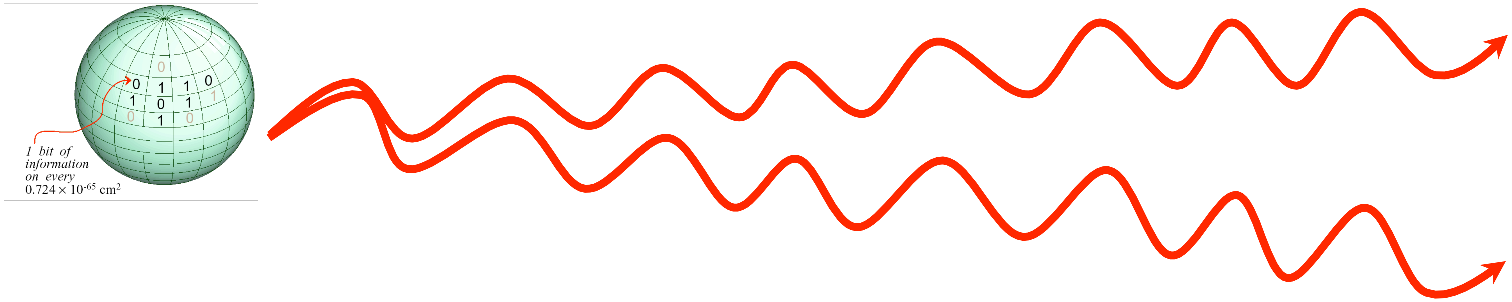
- Beckenstein, Bardeen et al. (~1972): laws of black hole thermodynamics
- Area of (null) event horizon, like entropy, always increases
- Entropy is identified with 1/4 of event horizon area in Planck units (not volume)
- Is there is a deep reason connected with microscopic degrees of freedom of spacetime encoded on the surface?

Holography 2: Black Hole Evaporation

- Hawking (1975): black holes radiate ~thermal radiation, lose energy and disappear
- evaporated quanta carry off degrees of freedom (~1 per particle) as area decreases
- States on 2D event horizon completely account for information of evaporated states, assembly histories
- Information of evaporated particles=entropy of hole= *A/4*

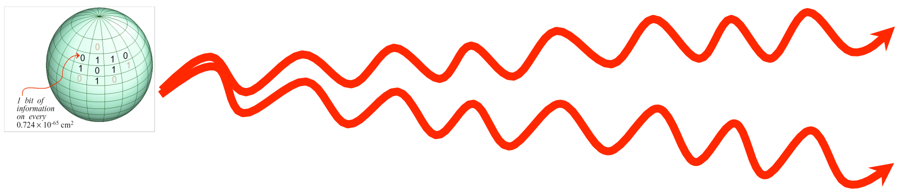


black hole evaporation can obey quantum mechanics only if distant flat space is indeterminate



If the quantum states of the evaporated particles allowed relative transverse position observables with arbitrary angular precision, at large distance they would contain more information than the hole

Holographic uncertainty and black hole evaporation



$$(L/\Delta x)^2 < (R/\lambda)^2$$

- ~ One particle evaporated per Planck area
- position recorded on film at distance *L*
- wavelength ~ hole size *R*
- standard position uncertainty

$$\Delta x > R$$

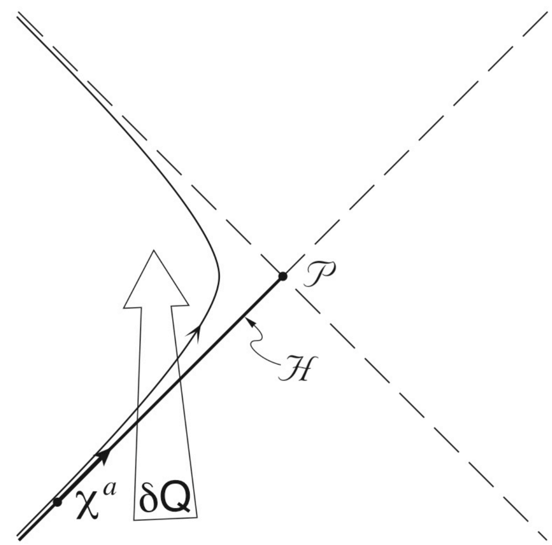
- Particle images on distant film: must have fewer “pixels” than hole
- Requires transverse uncertainty at distance *L* independent of *R*

$$\Delta x > \sqrt{\lambda L}$$

- Uncertainty of flat spacetime independent of hole
- Similarly for number of position states of an interferometer

Holography 3: nearly-flat spacetime

- Unruh (1976): Hawking radiation seen by accelerating observer
- Appears with any event horizon, not just black holes: identify entropy of thermal radiation with missing information
- Jacobson (1995): Einstein equation derived from thermodynamics (~ equation of state)
- Classical GR from 2+1D null surface (Padmanabhan 2007)



Jacobson: points=2D surfaces

Holography 4: Covariant (Holographic) Entropy Bounds

- 't Hooft (1985): black holes are quantum systems
- 't Hooft, Susskind et al. (~1993): world is "holographic", encoded in 2+1D at the Planck scale
- Black hole is highest entropy state (per volume) and sets bound on entropy of any system (includes quantum degrees of freedom of spacetime)
- All physics within a 3D volume can be encoded on a 2D bounding surface ("holographic principle")
- Bousso (2002): holographic principle generalized to "covariant entropy bound" based on causal diamonds: entropy of 3D light sheets bounded by area of 2D bounding surface in Planck units
- Suggests that 3+1D geometry emerges from a quantum theory in 2+1D: light sheets

Holography 5: Exact dual theories in N-1 dimensions

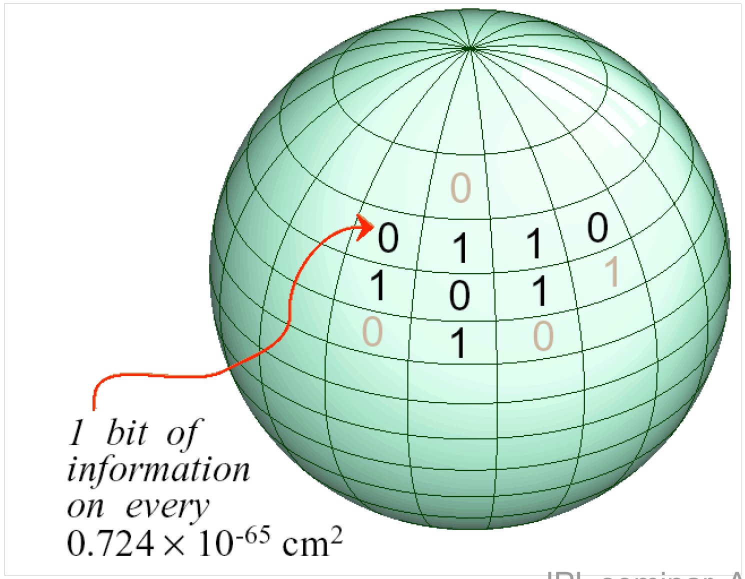
- Maldacena, Witten et al. (1997…): AdS/CFT correspondence
- N dimensional conformal field "boundary" theory exactly maps onto (is dual to) N+1 dimensional "bulk" theory with gravity and supersymmetric field theory
- Is nearly flat 3+1 spacetime described as a dual in 2+1?

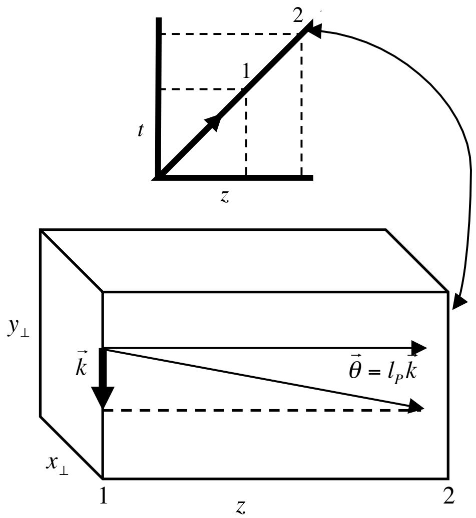
Holography 6: string/M theory

- Strominger, Vafa (1996): count degrees of freedom of extremal higher-dimension black holes using duality
- All degrees of freedom appear accounted for
- Agrees with Hawking/Beckenstein thermodynamic count
- Unitary quantum system
- Strong indication of a minimum length ~ Planck length
- What do the degrees of freedom look like in a realistic system?
- Matrix theory: wavefunctions of transverse position Matrix Hamiltonian (CJH& M. Jackson)

Holographic geometry implements holographic entropy bound in emergent 3+1D spacetime

- 3+1D spacetime from 2+1D theory
- built on light sheets: covariant formulation
- fewer independent modes than field theory
- independent pixels in 3D volume~ area of 2D null surface element
- "bandwidth limit" of spacetime states





Theories with holographic noise

Two conditions are sufficient:

1. Maximum Planck frequency in any frame
2. Planck wavelength resolution on light sheets

Count degrees of freedom with Shannon/Nyquist sampling: 2 degrees of freedom per wavelength

1D segment of length *L* on null wavefront

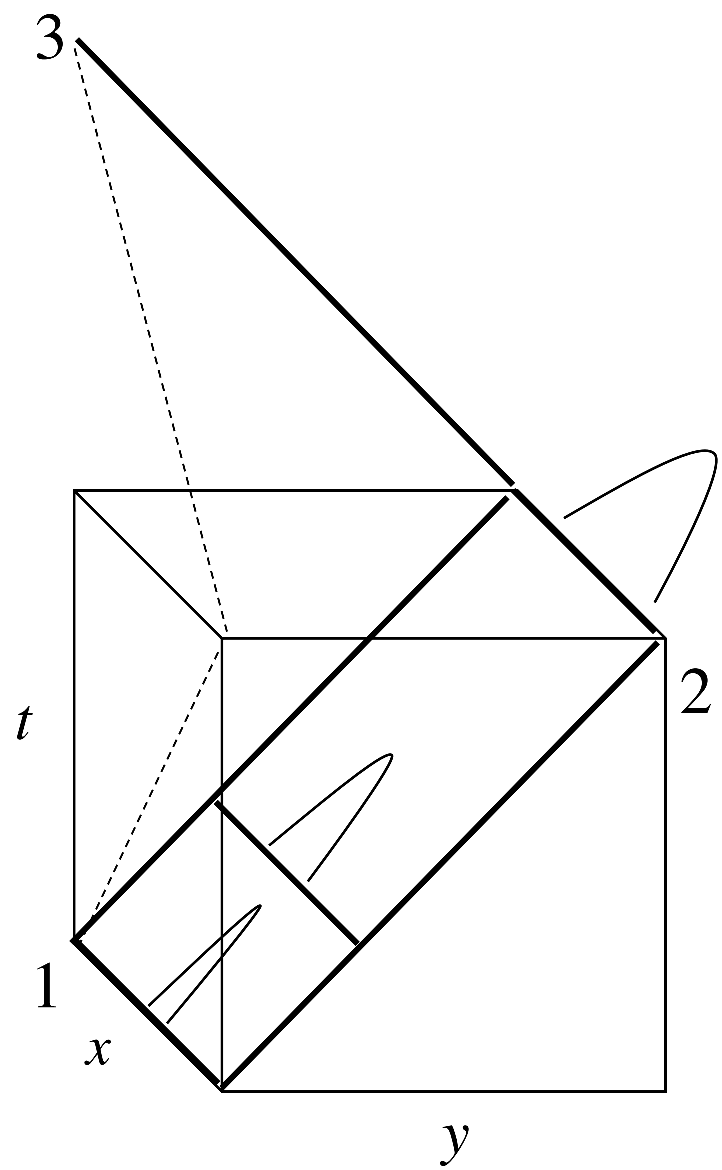
Sweeps out 2D surface:

$$(L/\Delta x)^2 \approx L/l_P$$

independent position degrees of freedom

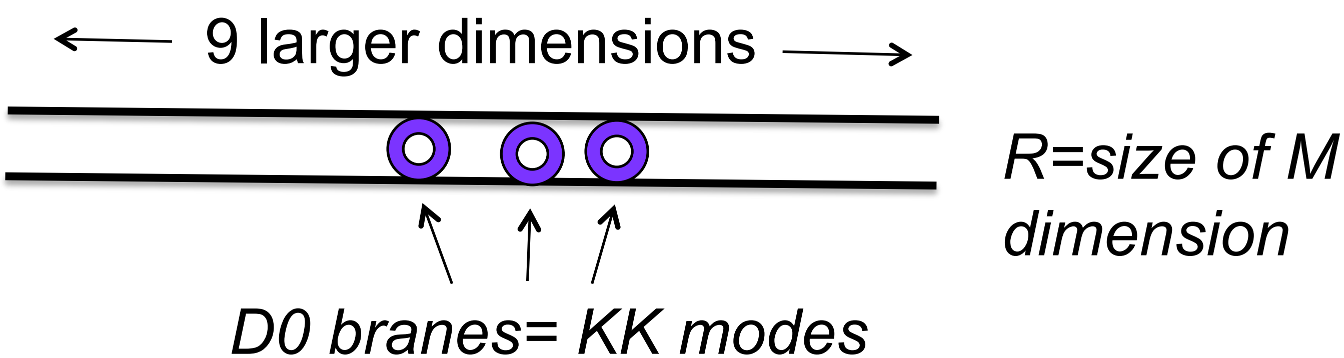
Position variance in 2D

$$\Delta x^2 \approx L l_P$$



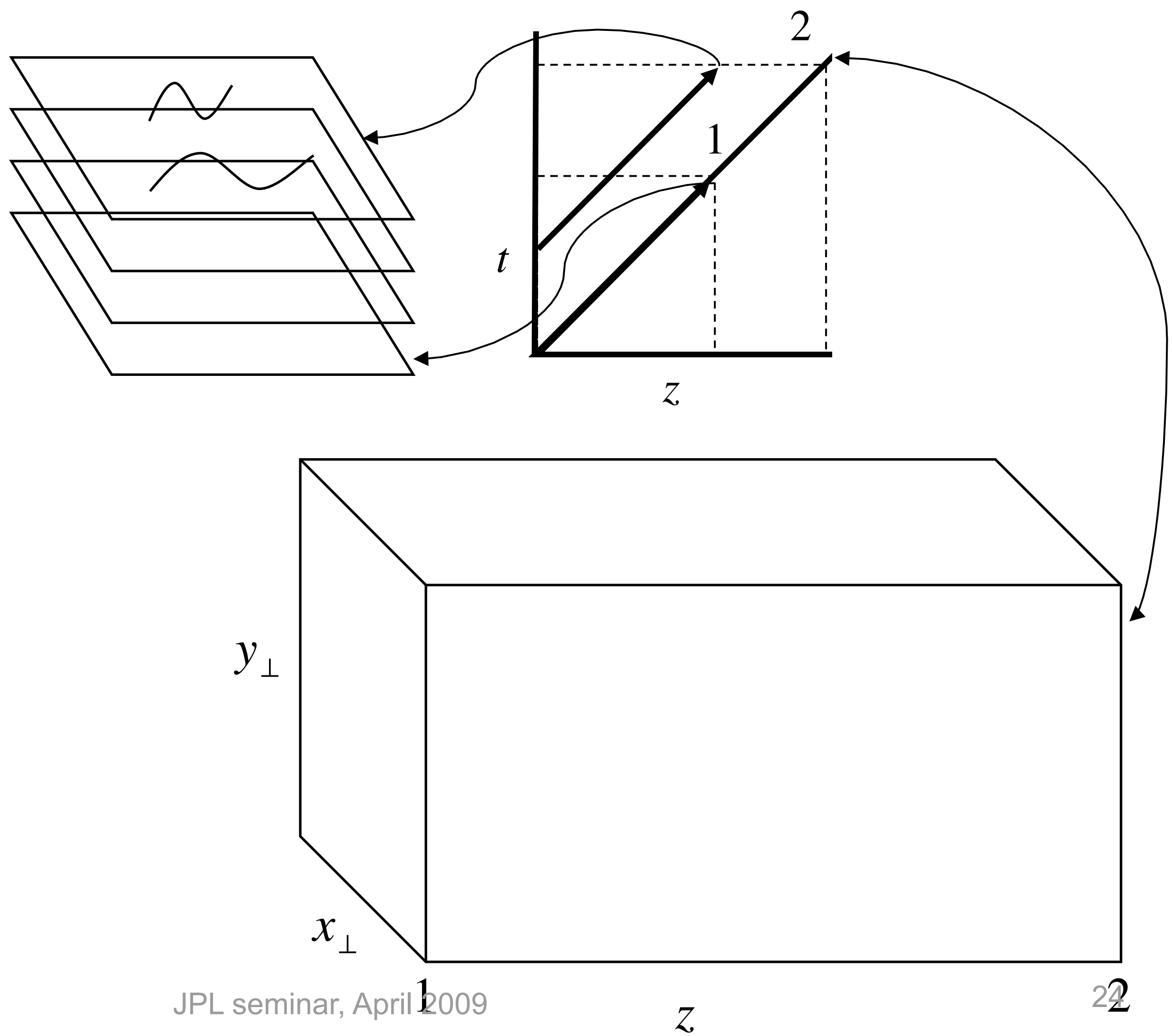
Example: Matrix theory

- Banks, Fischler, Shenker, & Susskind 1997: a candidate theory of everything
- Fundamental objects are 9 N x N matrices, describing N “D0 branes” (particles)
- Dual relationship with string theory
- Gives rise to 10 space dimensions, 1 compact, plus time



- Only 2 of the 9 space dimensions survive to be macroscopic
- The third space dimension is virtual, swept out by 2D null sheet
- Einstein's "ride on a photon": what does the world look like?

3+1D spacetime emerges from 2+1D: light sheet with z=t



Holographic spacetime: wave theory from M theory

- N D0 branes, N x N matrices X_i, , i= 1 to 9, compact M dimension with radius R ~ Planck length
- Hamiltonian from Banks, Fischler, Shenker, & Susskind:

$$H = R\ \mathrm{tr}\ \left\{ \frac{\Pi_i \Pi_i}{2} + \frac{1}{4}[X_i, X_j]^2 + \theta^T \gamma_i [\theta, X_i] \right\}$$

- Notions of position, distance emerge on scales >>R
- local in 2+1 D, “incompressible” on Planck scale: holographic
- Center of mass position of macroscopic body, x= tr X
- Macroscopic longitudinal position encoded by first (kinetic) term,conjugate momenta to position matrices

CJH & M. Jackson, arXiv:0812.1285

Macroscopic wave equation from M theory

- M Hamiltonian

$$H = \frac{R}{\hbar}\,\mathrm{tr}\,\sum_i \left\{ \frac{\Pi_i \Pi_i}{2} + \sum_j \frac{1}{4}[X^i, X^j]^2 \right\}$$

- Leads to wave equation in each transverse dimension *x*

$$\frac{\partial^2 u}{\partial x^2} + \frac{2i}{R}\frac{\partial u}{\partial z^+} = 0$$

- Quantum mechanics without Planck's constant
- Schrodinger equation
- Solutions display diffusion, diffraction

Paraxial wave equation

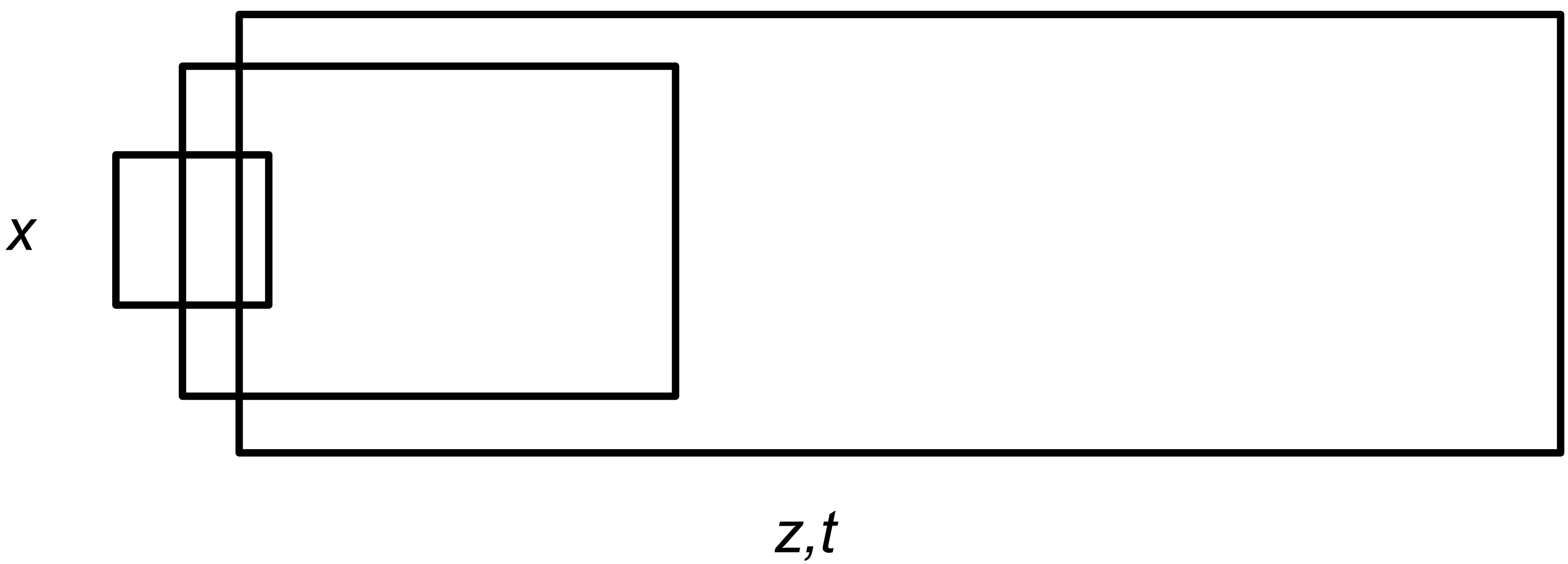
- phasors in wavefronts
- wave equation in each transverse dimension *x*

$$\frac{\partial^2 u}{\partial x^2} - \frac{2i}{R}\frac{\partial u}{\partial z^+} = 0$$

- "Paraxial Wave Equation:" generic, quasi-optical behavior
- Solutions display diffraction: e.g. laser cavities

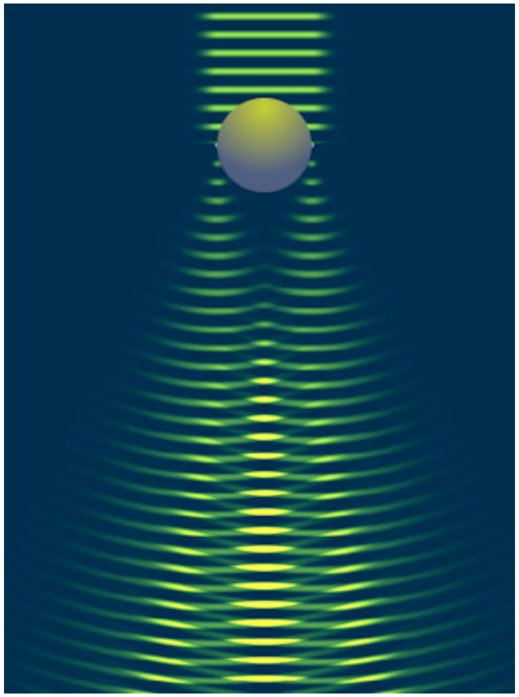
Nonlocal modes connect longitudinal and transverse positions

- Wave solutions: “Holographic geometry”
- Transverse gaussian beam solutions from wave optics
- New macroscopic behavior, not the same as field theory limit



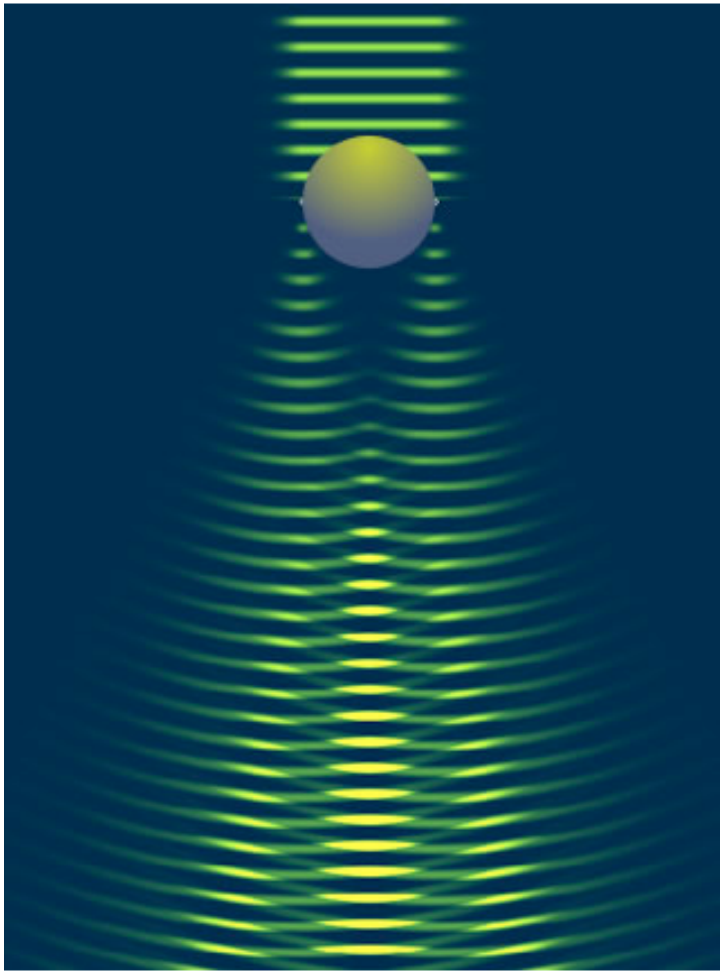
Holographic Geometry

- Spacetime is made of waves, not a continuous classical manifold
- theory built on light sheets
- “Planck photon’s view” of the world

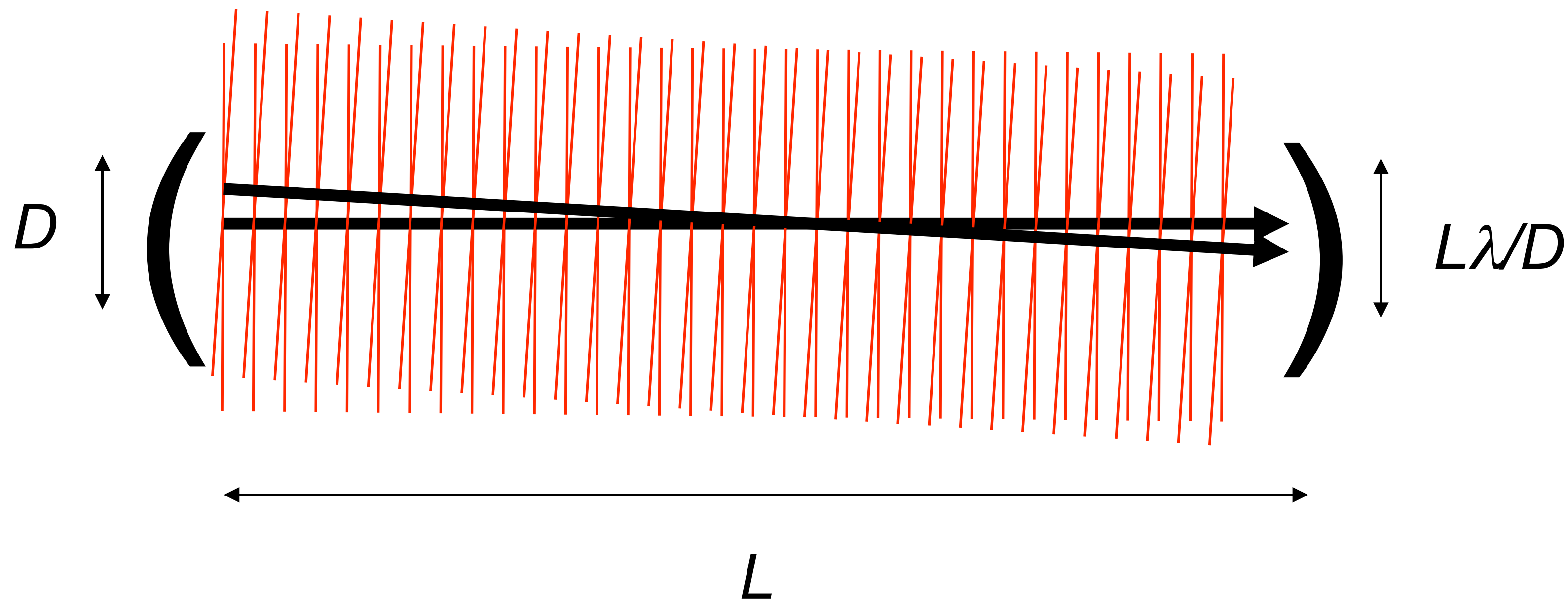


Wave Theory of Spacetime

- Adapt wave optics to theory of "spacetime wavefunctions"
- transverse indeterminacy from diffraction of Planck waves
- Allows calculation of holographic noise with no parameters



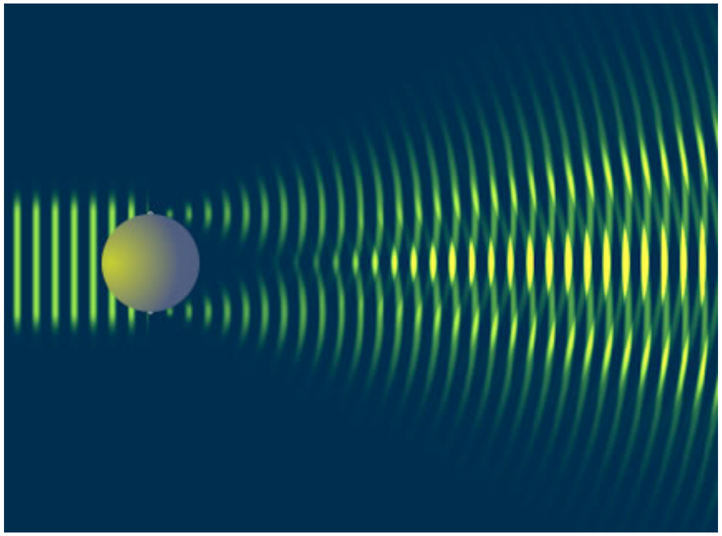
Rayleigh range and uncertainty of rays

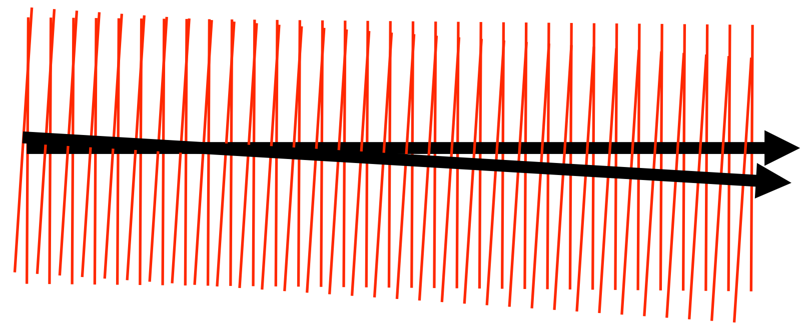


- Aperture *D*, wavelength λ *:* angular resolution λ/D
- Size of diffraction spot at distance *L: L*λ/D
- path is determined imprecisely by waves
- Minimum uncertainty at given *L* when aperture size =spot size, or

$$D = \sqrt{\lambda L}$$

Indeterminacy of a Planckian path





- Classical spacetime manifold defined by paths and events
- path~ ray approximation of wave
- Indeterminacy of geometry reflects limited information content of band-limited waves

Uncertainty of transverse position

***Wavefunctions of wavefronts**: Transverse positions at normal separation L have standard deviations related by:*

$$\sigma'\sigma = \lambda L$$

For macroscopic L the uncertainty is much larger than the wavelength

Controlled theory based on wave optics:
CJH, arXiv: **0806.0665**

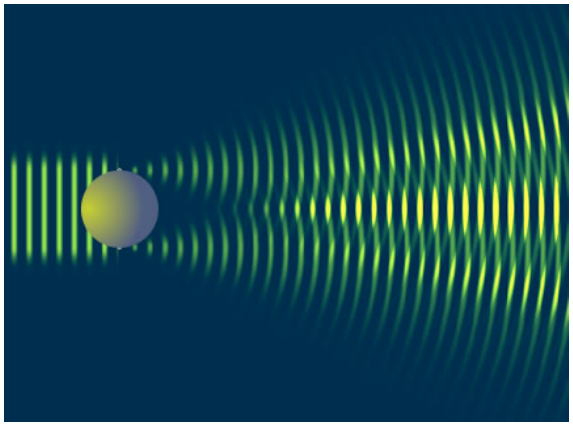
holographic approach to the classical limit

- Angles are indeterminate at the Planck scale, and become better defined at larger separations:

$$\Delta\theta(L) = (l_P/L)^{1/2}$$

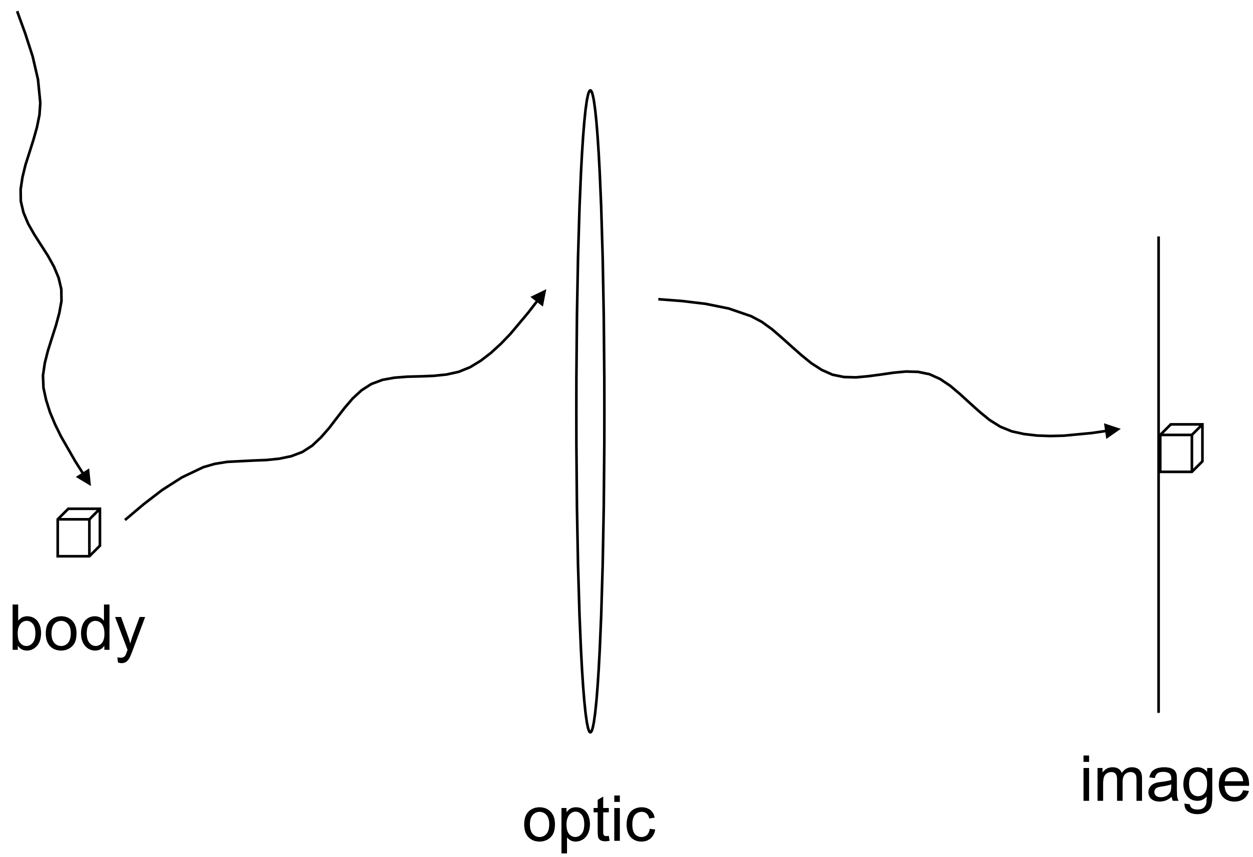
- But uncertainty in relative transverse position **increases** at larger separations:

$$\Delta x_\perp^2 > l_P L$$



- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

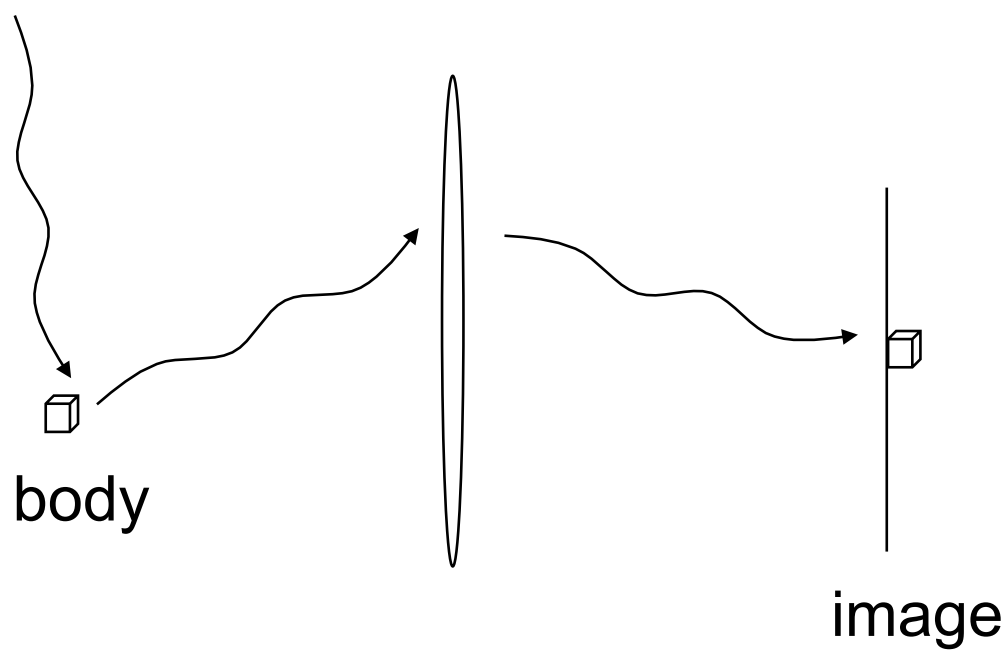
"Heisenberg microscope"



Δ(measured position) x Δ(momentum of perturbation)> hbar/2

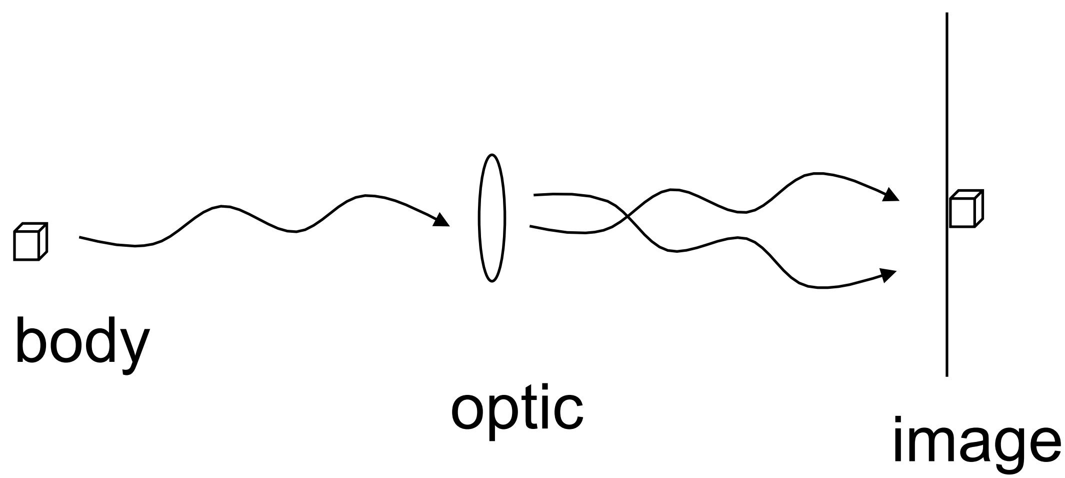
Heisenberg Microscope

- Measures transverse position by imaging using scattered light
- Uncertainty relation between measured position, transverse photon momentum
- observables do not have independent classical meaning



"Planck telescope"

- Create “image” on a screen
- Wavelength = Planck
- Minimum uncertainty in angle or transverse position difference when size of optic ~ size of its own diffraction spot
- Wavefronts can’t transport or encode more transverse information
- Transverse positions of body, optic, image, do not have independent classical meaning



Uncertainty: Heisenberg and Holographic

- "Heisenberg microscope": transverse position of a remote body measured by angular position~ detected position of radiation particle in image
- Fixed 3D classical space
- Δ(measured transverse position of a body) x Δ(momentum of measuring radiation) > hbar/2
- Δ independent of microscope aperture, focal length; depends on mass of body
- State of body, radiation depends on measurement

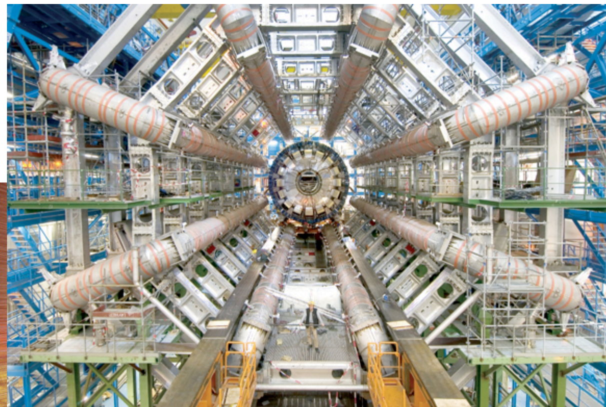
- "Planck telescope": remote transverse positions measured by Planck radiation
- Fixed wavelength in a given frame
- Δ(position 1) x Δ(position 2) > (Planck length) x (separation)
- Δ position depends on separation, independent of mass
- Property of holographic spacetime geometry: limiting precision of Planck waves
- State of position of everything depends on measurement

Holographic Noise in Interferometers

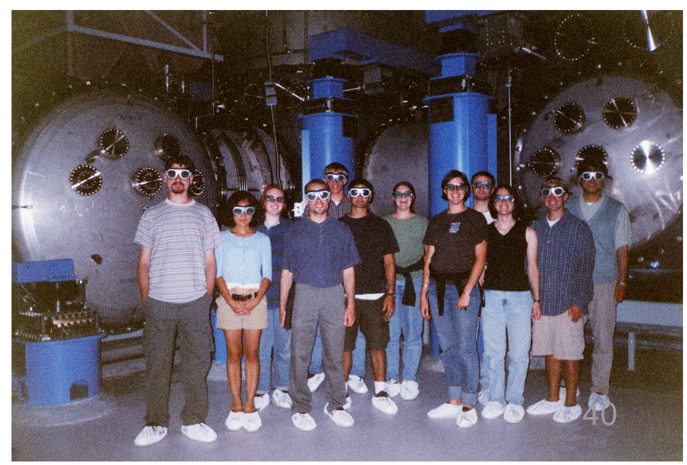
- Nonlocality: relative positions at km scale
- Fractional precision: angle < 10^{-21}, > "halfway to Planck"
- Transverse position measured in Michelson layout
- Heavy proof masses, small Heisenberg uncertainty (SQL): positions measure spacetime wavefunction
- holographic noise appears in signal

Measurement of holographic geometry requires coherent transverse position measurement over macroscopic distance

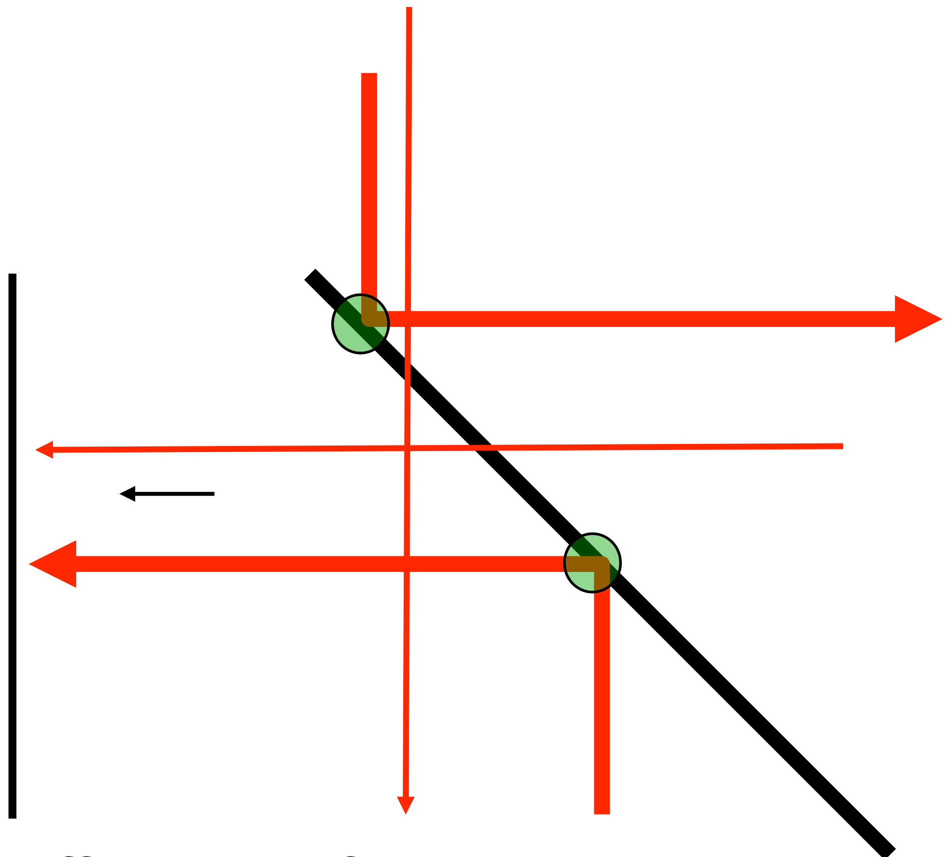
CERN/FNAL: $\mathrm{TeV}^{-1} \sim 10^{-18}$ m



LIGO/GEO: $\sim 10^{-18}$ m
over $\sim 10^{3}$ m baseline



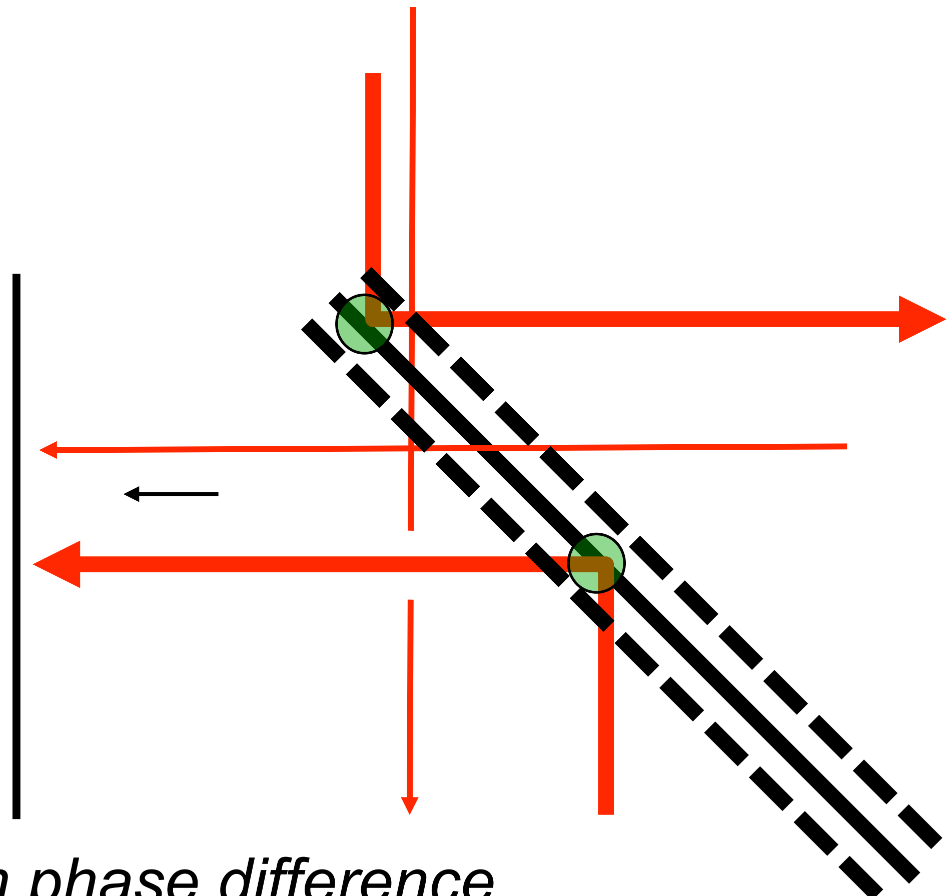
Beamsplitter and signal in Michelson interferometer



Signal phase~ difference of integrated distance along two orthogonal arms

Beamsplitter

Holographic noise in the signal of a Michelson interferometer



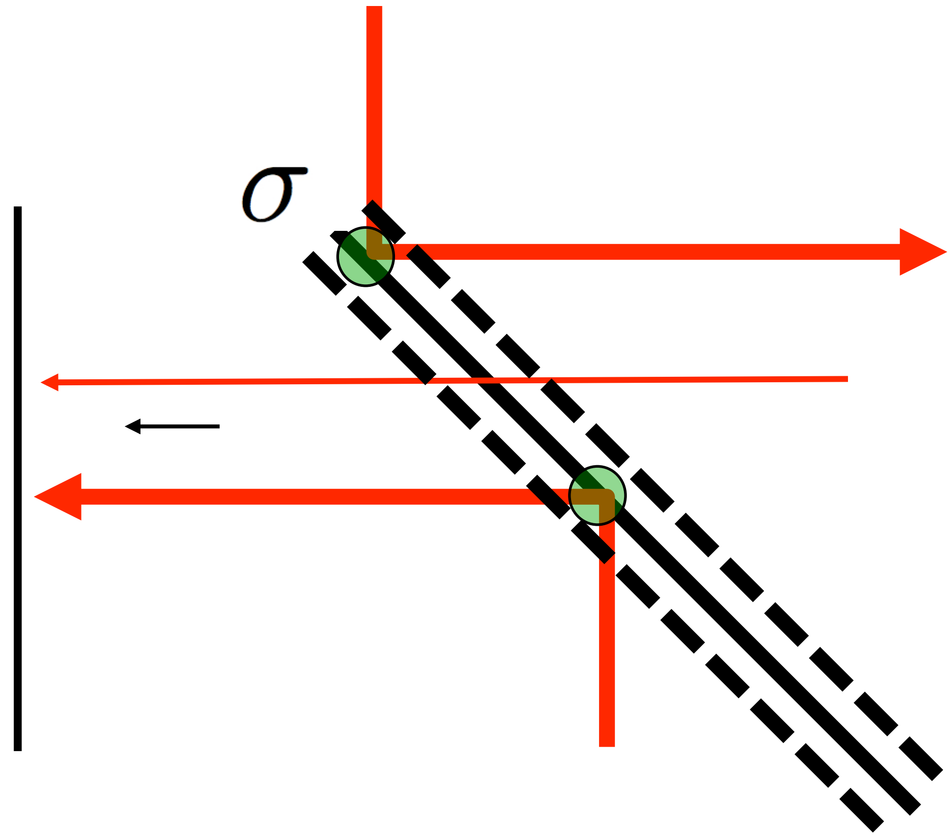
reflection events at two times separated by $L=2L_0$

Signal: random phase difference of reflection events from indeterminate position difference of beamsplitter at the two events

Quantum uncertainty of transverse positions of beamsplitter

- Position wavefunction widths of beamsplittter at reflection events related by

$$\sigma'\sigma = \lambda L$$



- apparent arm length difference is a random variable, with variance:

$$\Delta L_0^2 = \sigma^2 + {\sigma'}^2 = 2\sigma^2 = 4 l_P L_0$$

this is a new effect predicted with no parameters

Power Spectral Density of Shear Noise

Uncertainty in angle ~ dimensionless shear

$$\Delta\theta(L) = (l_P/L)^{1/2}$$

At f=c/2L, shear fluctuations with power spectral density

$$h_H^2 \simeq L\Delta\theta^2 \approx t_P$$

h_H^2 =mean square perturbation per frequency interval

(no parameters, Planck length is the only scale)

Universal Holographic Noise

*flat power spectral density of **shear** perturbations:*

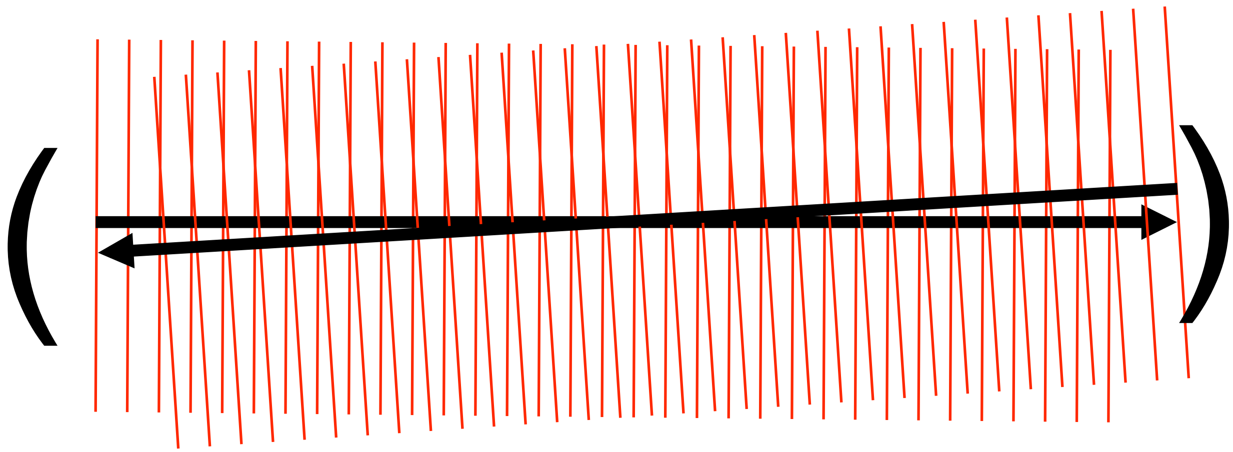
$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22} \mathrm{Hz}^{-1/2}$$

- general property of holographic quantum geometry
- Prediction of spectrum with no parameters
- Prediction of spatial shear character: only detectable in transverse position observables
- Definitively falsifiable

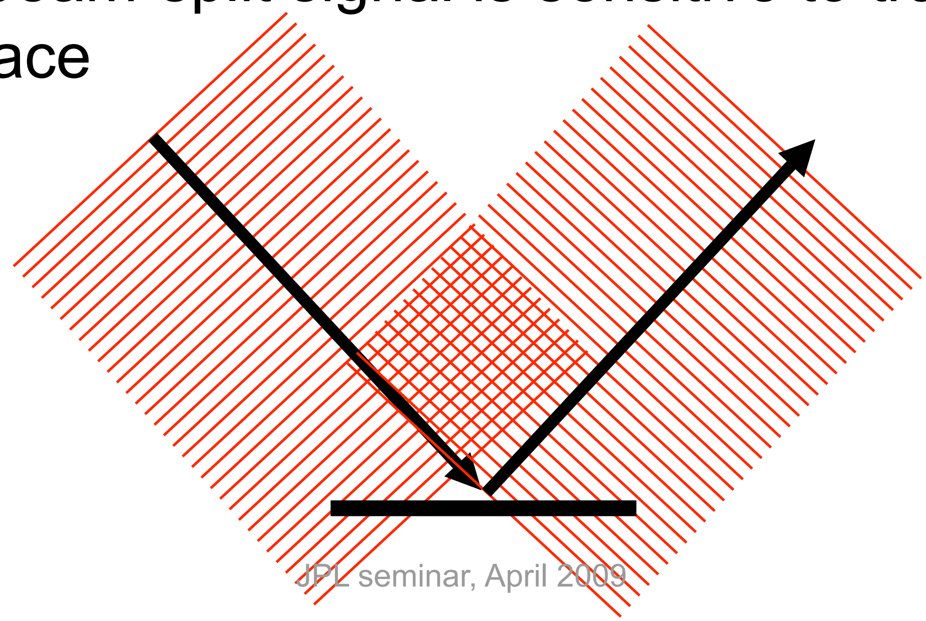
Holographic noise does not carry energy or information

- ~ classical gauge mode (flat space, no classical spacetime degrees of freedom excited)
- ~sampling or pixelation noise, not thermal noise
- Bandwidth limit of spacetime relationships
- Necessary so the number of distinguishable positions does not exceed holographic bound on degrees of freedom
- No curvature
- no strain, just shear
- no detectable effect in a purely radial measurement

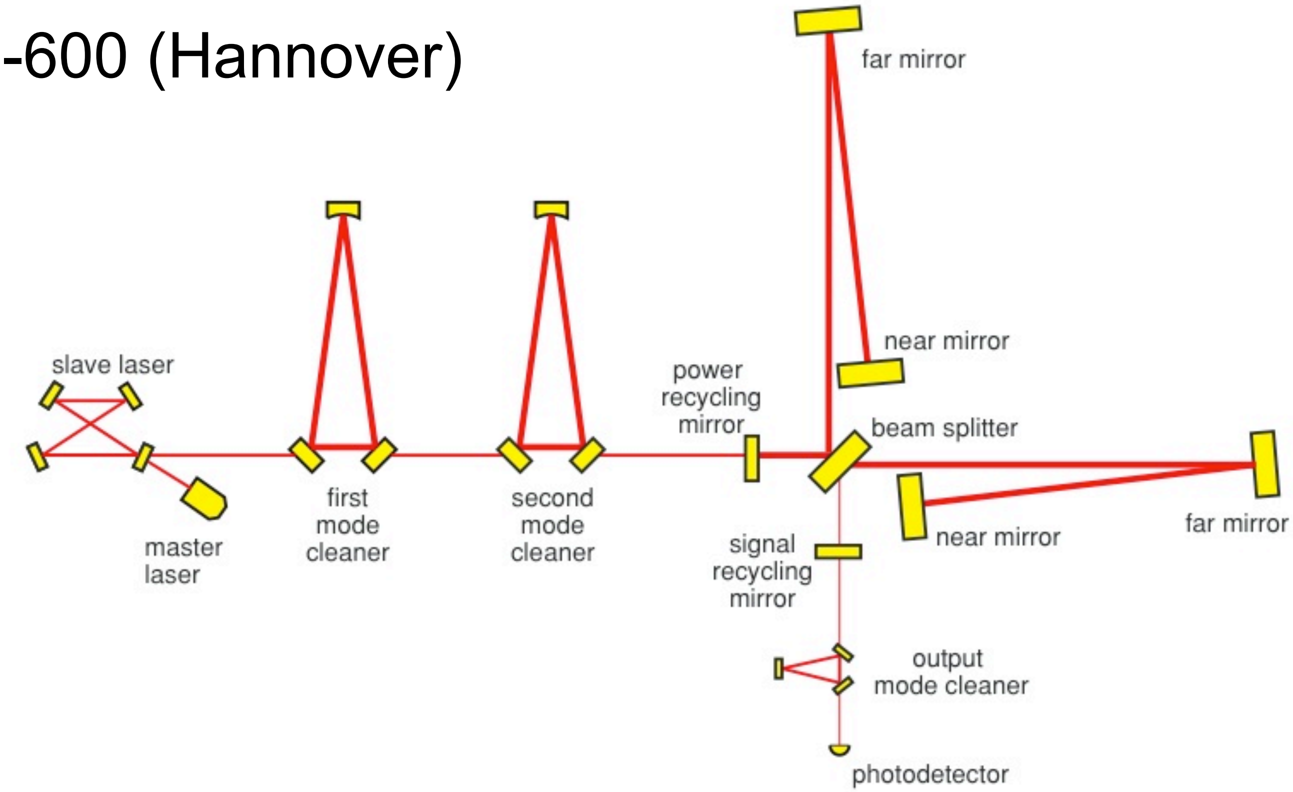
Normal incidence optics: phase signal does not record the transverse position of a surface



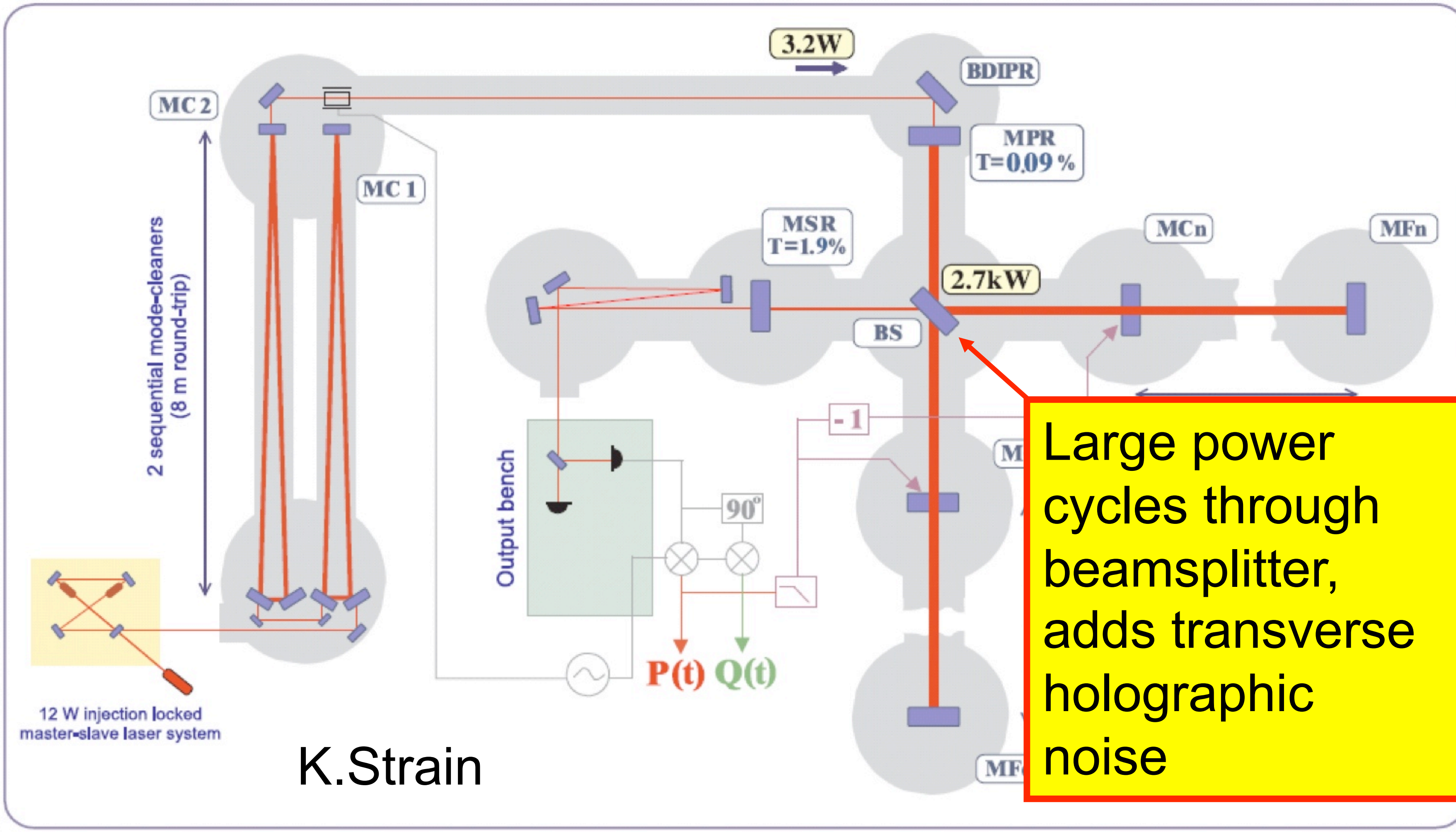
- But phase of beam-split signal is sensitive to transverse position of surface



GEO-600 (Hannover)



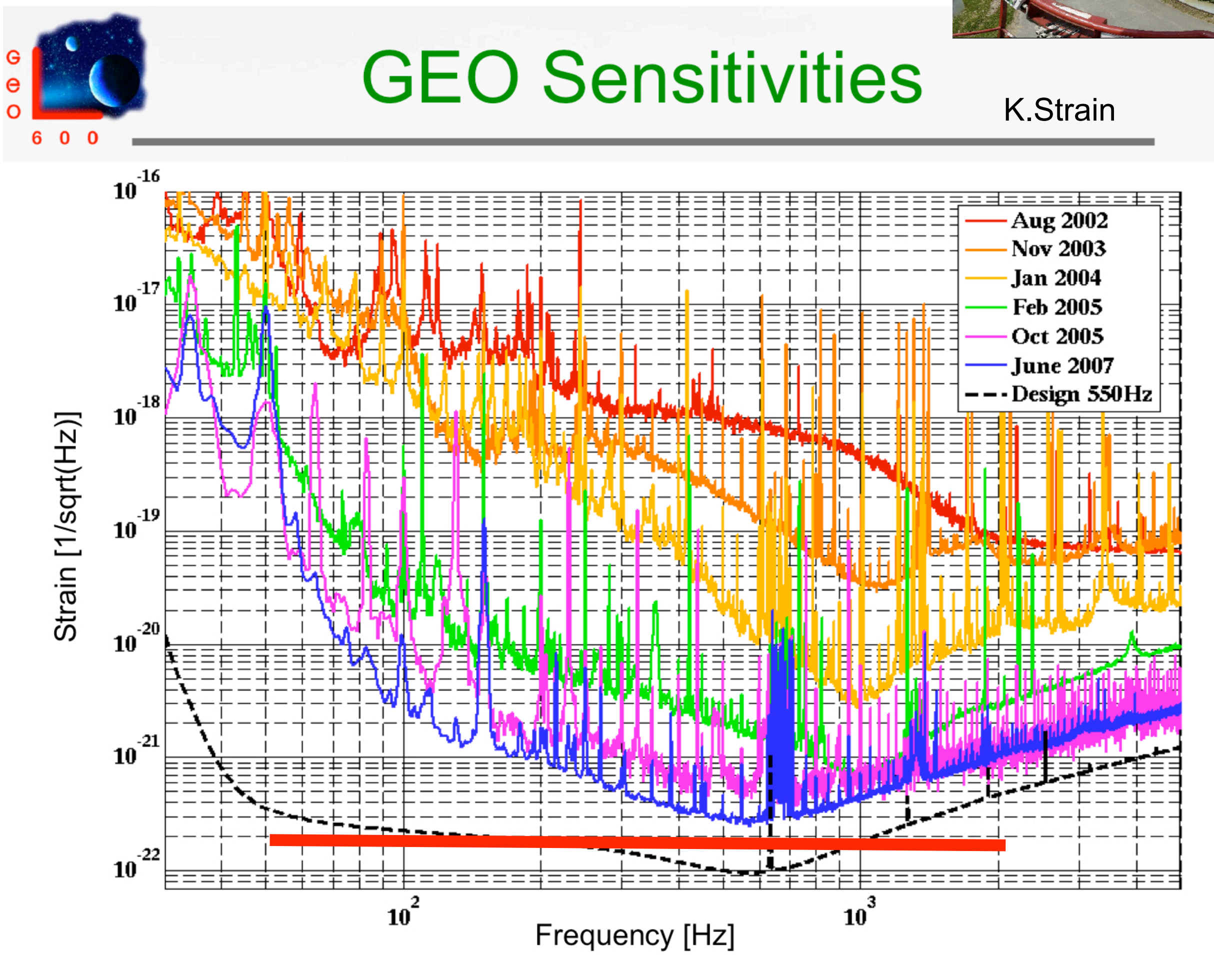
The GEO600 Interferometer

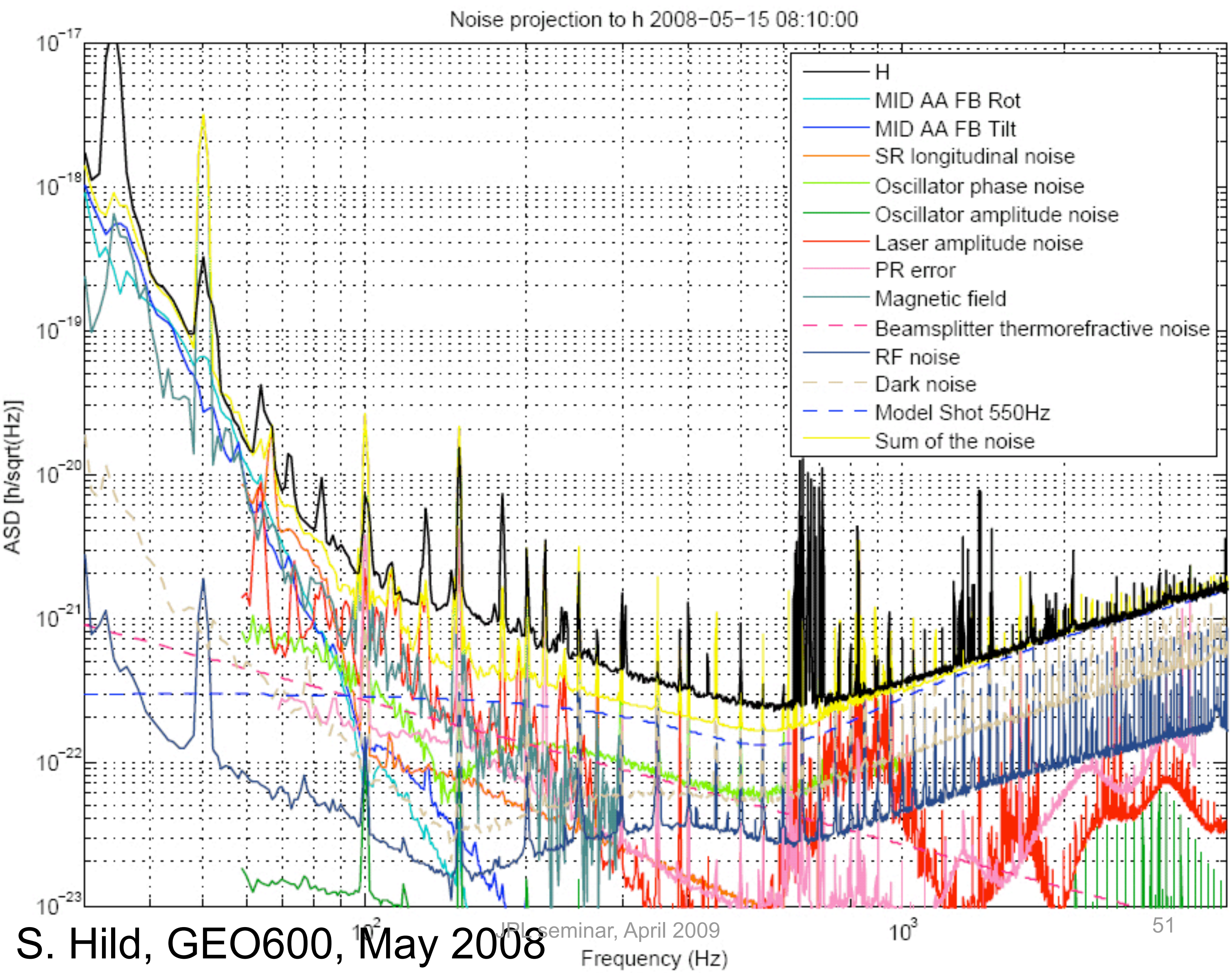


K.Strain

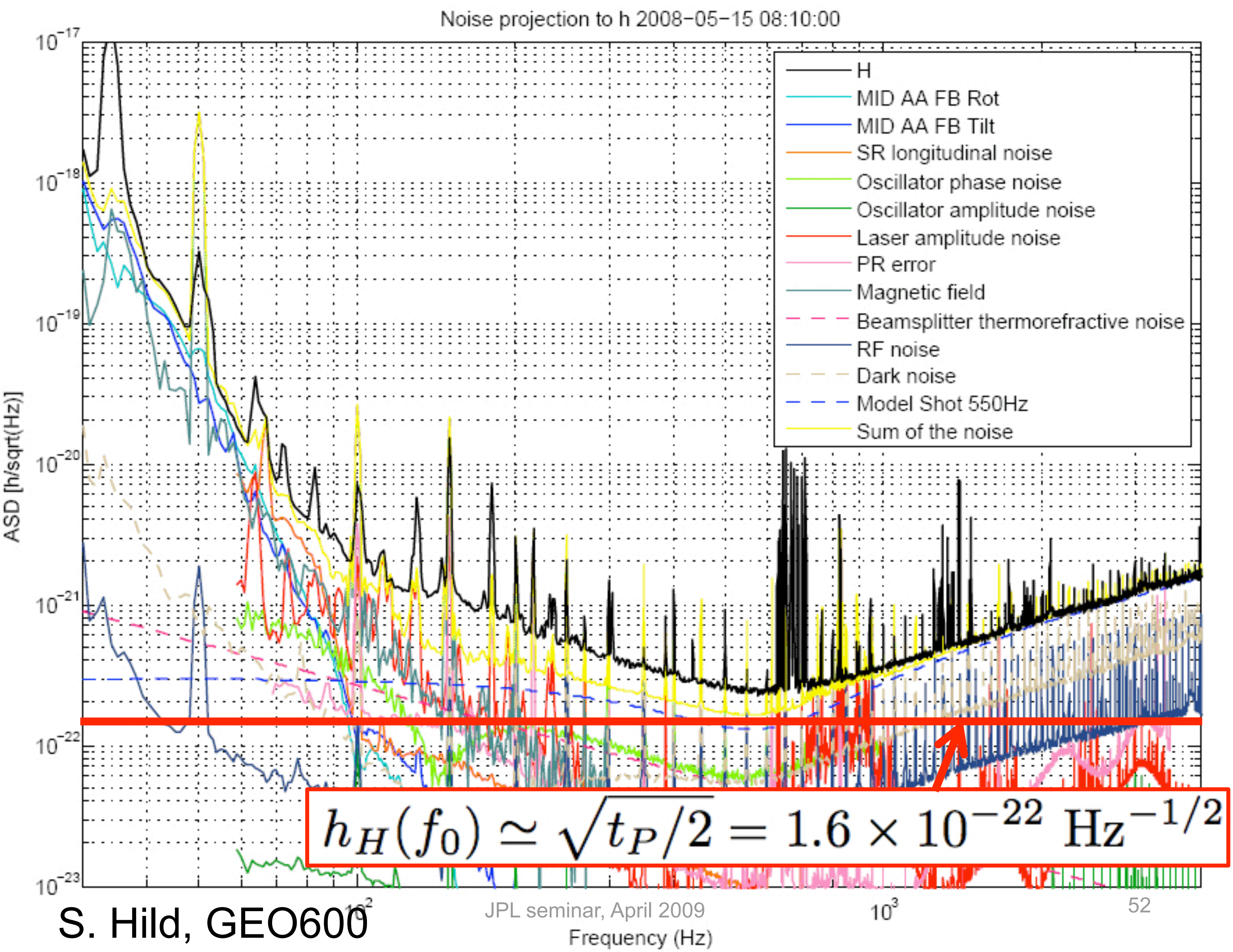
Large power cycles through beamsplitter, adds transverse holographic noise

Noise in GEO600 over time



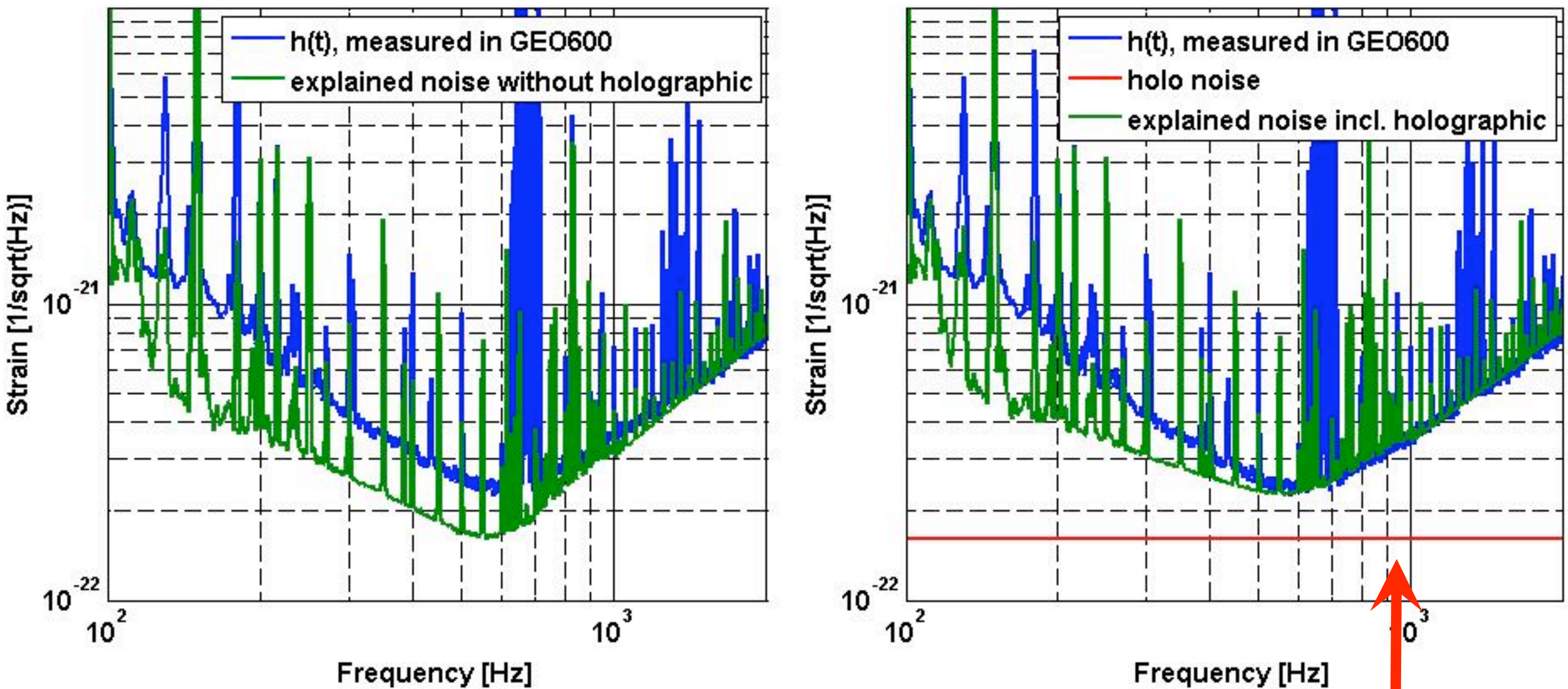


S. Hild, GEO600, May 2008



S. Hild, GEO600

“Mystery Noise” in GEO600



$$\sqrt{t_{Planck}/2}$$

Data: S. Hild (GEO600)

zero-parameter prediction for holographic noise in GEO600 (equivalent GW strain)

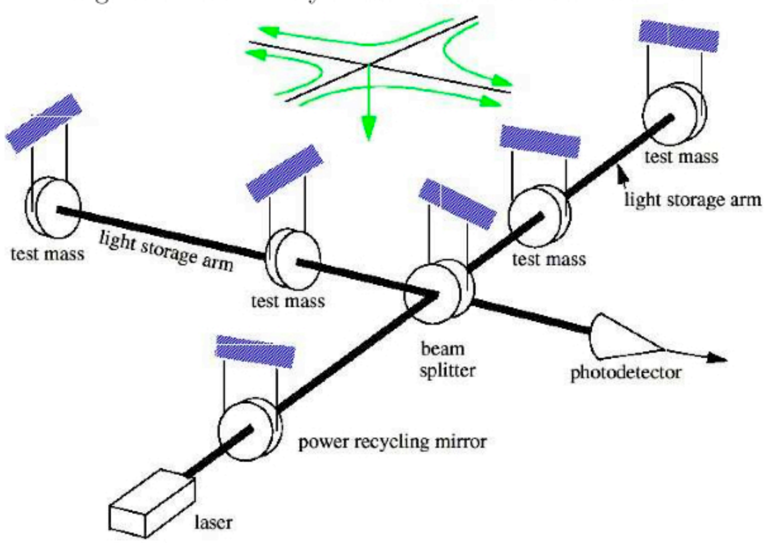
Prediction: CJH, arXiv:0806.0665
(Phys Rev D.78.087501)

Total noise: not fitted

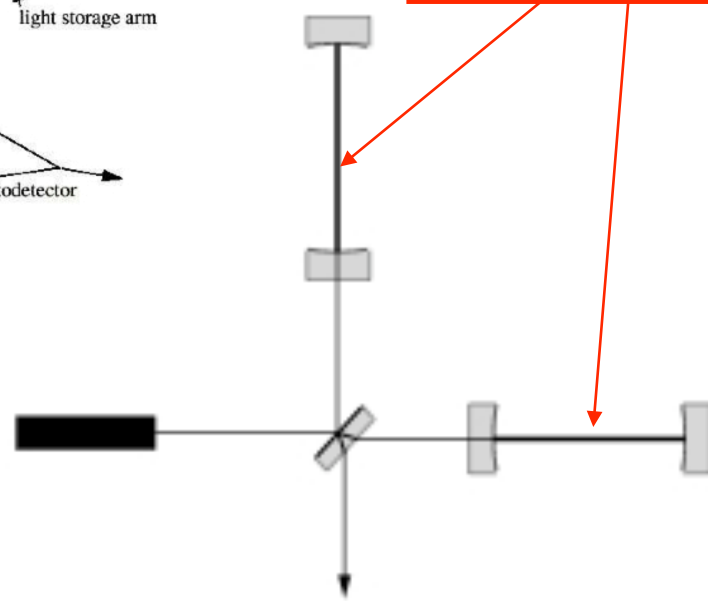
Why doesn't LIGO detect holographic noise?

- LIGO design is not as sensitive to transverse displacement noise as GEO600
- relationship of holographic to gravitational wave depends on details of the system layout

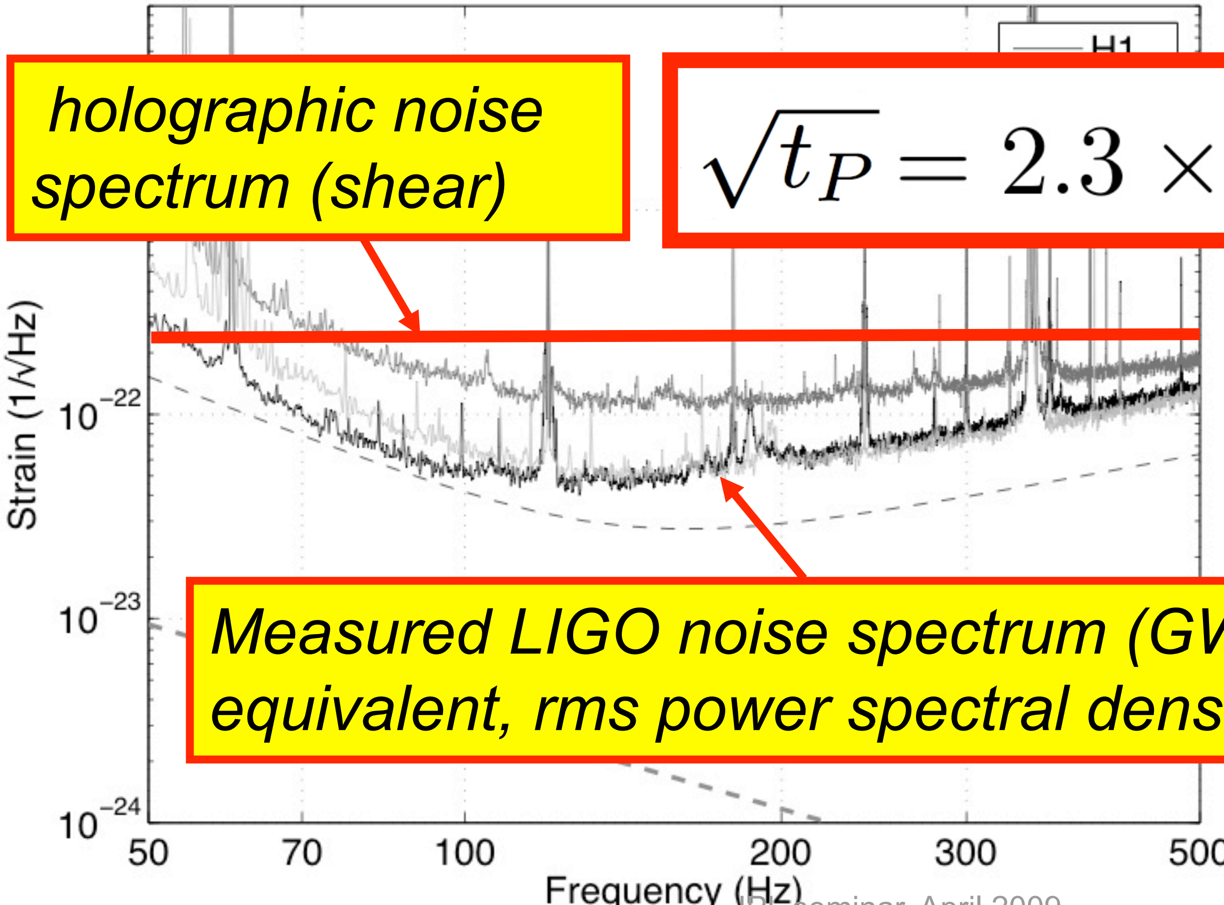
Fig. 1. Schematic layout of a LIGO interferometer.



Transverse position measurement is not made in FP cavities



LIGO noise (astro-ph/0608606)



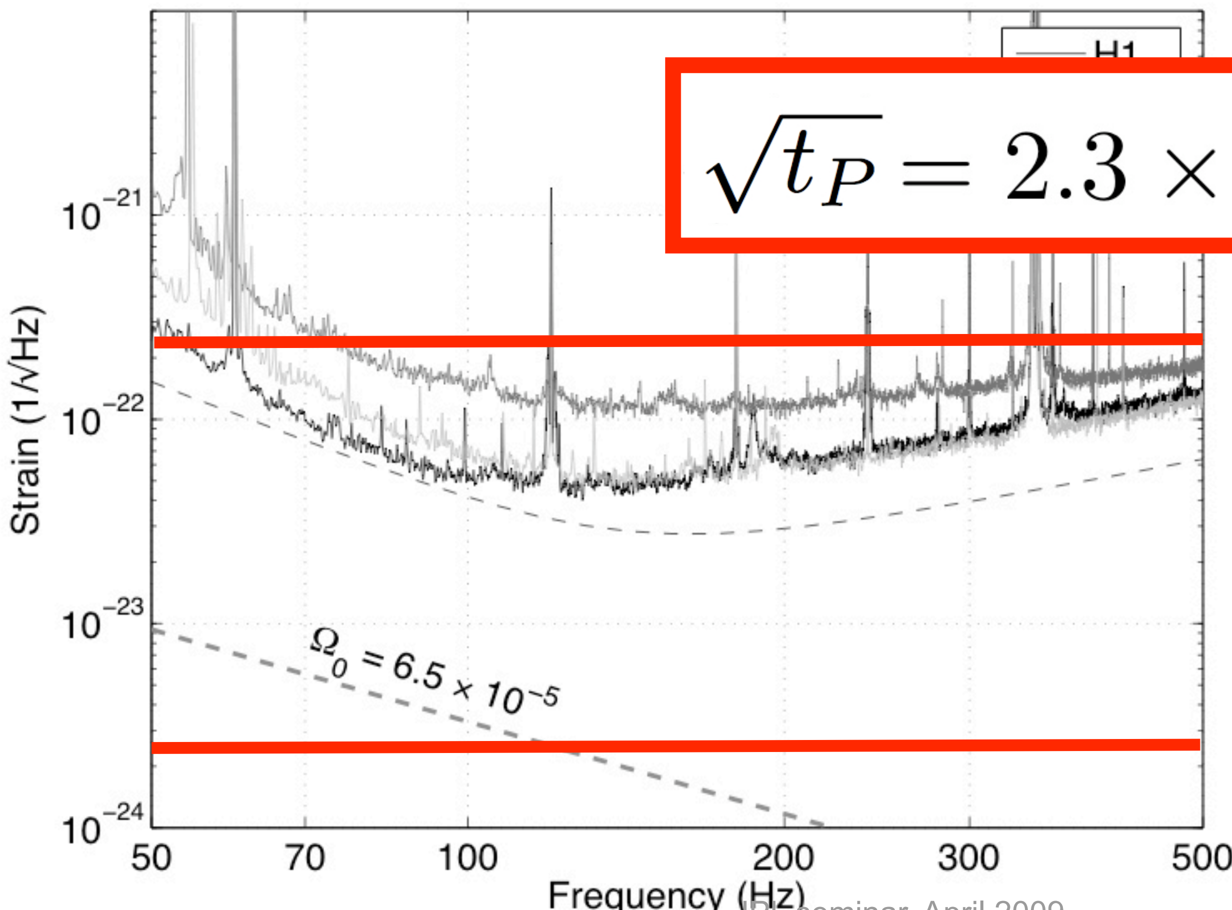
holographic noise spectrum (shear)

$$\sqrt{t_P} = 2.3 \times 10^{-22} / \sqrt{\mathrm{Hz}}$$

(if shear=strain)

Measured LIGO noise spectrum (GW strain equivalent, rms power spectral density)

LIGO noise, and holographic noise prediction based on arm cavity finesse



$$\sqrt{t_P} = 2.3 \times 10^{-22} / \sqrt{\mathrm{Hz}}$$

about 100 times less

Interferometers can detect quantum indeterminacy of holographic geometry

- Beamsplitter position indeterminacy inserts holographic noise into signal
- **system with GEO600 technology can detect holographic noise if it exists**
- Signatures: spectrum, spatial shear

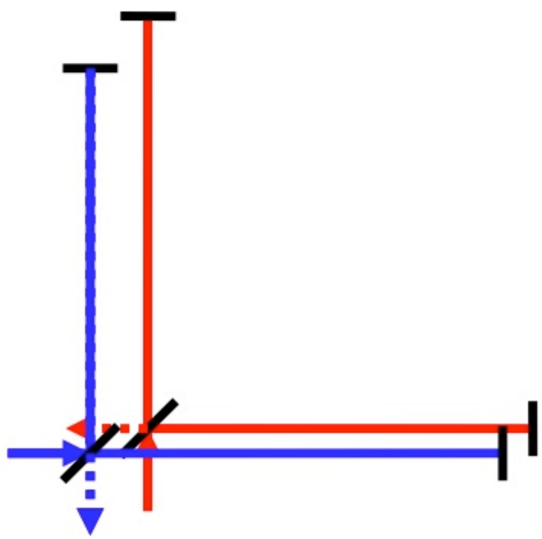
CJH: Phys. Rev. D 77, 104031 (2008); **arXiv:0806.0665**

Current experiments: summary

- Most sensitive device, GEO600, sees noise compatible with holographic spacetime indeterminacy
- requires testing and confirmation!
- H. Lück: "...it is way too early to claim we might have seen something.”
- But GEO600 is operating at holographic noise limit
- LIGO: current system not sensitive enough, awaits upgrade
- Followup possible at higher frequency
- Proof: new apparatus, coherence of adjacent systems

Dedicated holographic noise experiments: beyond GW detectors

- f ~100 to 1000 Hz with GW machines
- f ~ MHz possible with new apparatus on ~40m scale
- Easier suspension, isolation, optics, vacuum, smaller scale
- Correlated holographic noise in adjacent paths: signature of holographic effect

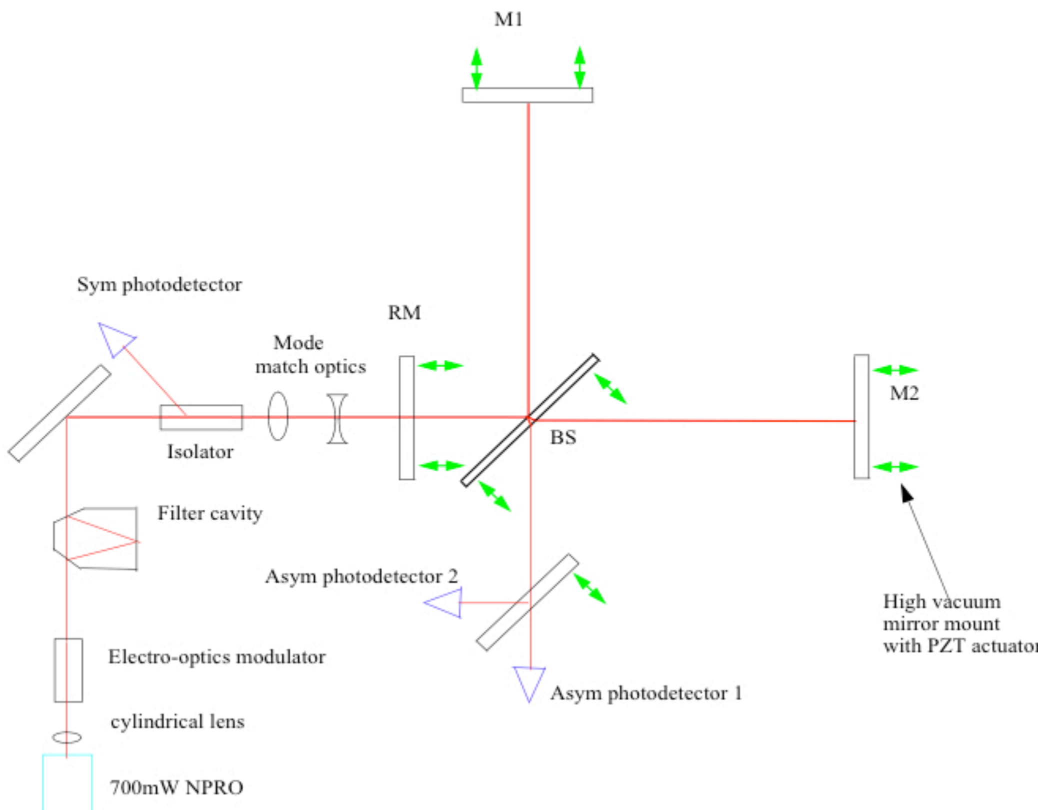


Conceptual Design from Rai Weiss

Two ~40m Michelson interferometers in coincidence

~1000 W cavity

holographic noise= laser photon shot noise in ~5 minutes (1 sigma)



Currently discussing: Fermilab (CJH, Chou, Wester, Steffen, Ramberg, Gustafson, Tomlin), MIT (Weiss, Waldman), Caltech (Whitcomb, Ballmer), AEI (Danzmann, Lück, Hild, Grote), UC (Meyer)

Next Steps

- GEO600 upgrades/retuning/ sample at free spectral range (125 kHz)
- Experiment at MHz frequencies for a convincing test
- Future: other technologies for measuring high precision, low noise, nonlocal relative transverse positions (e.g., atom interferometers)

Experimental science of holographic noise

- Measure fundamental interval of time
- Measure all physical degrees of freedom: explore physics "from above"
- Compare with Planck time derived from Newton's *G:* test fundamental theory
- Test predictions for spectrum and spatial correlations: properties of holographic geometry
- Connect with quantum physics of Dark Energy, inflationary fluctuations

Holographic geometry: part of new dark energy physics?

- Holographic blurring is ~0.1mm at the Hubble length
- ~(0.1mm)^-4 is the dark energy density
- “Nonlocality length” for dark energy is holographic displacement uncertainty, scaled to Hubble length
- (literature on “holographic dark energy” centers on same numerology)
- Does not “explain” dark energy!